Precision Reactor $\bar{\nu}_e$ Spectrum Measurements: Recent Results and PROSPECTs

April 16, 2014

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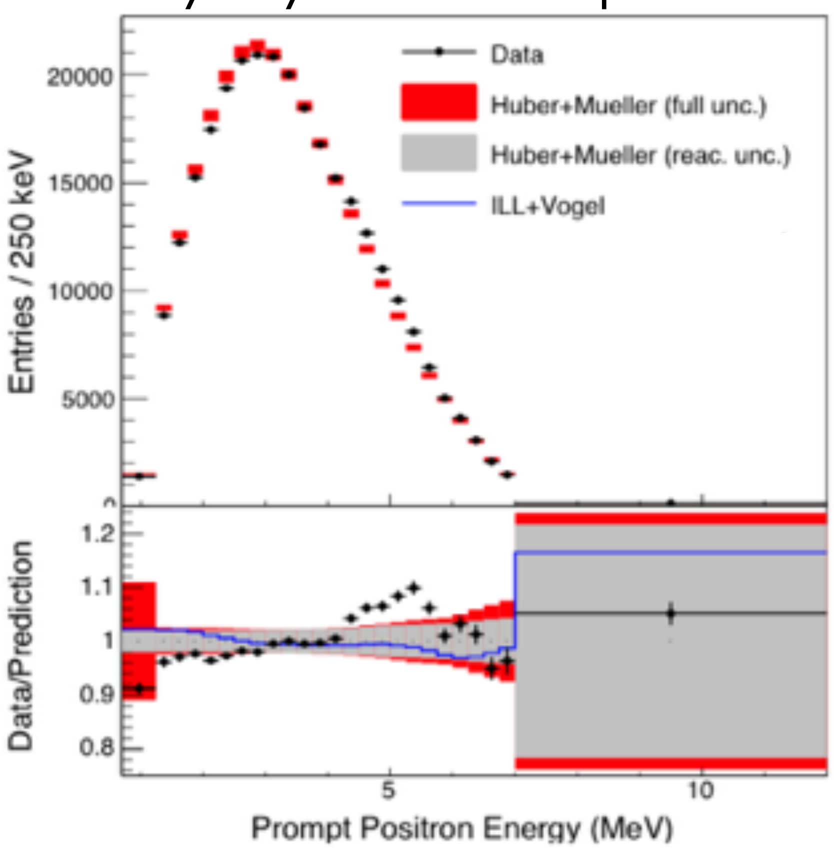
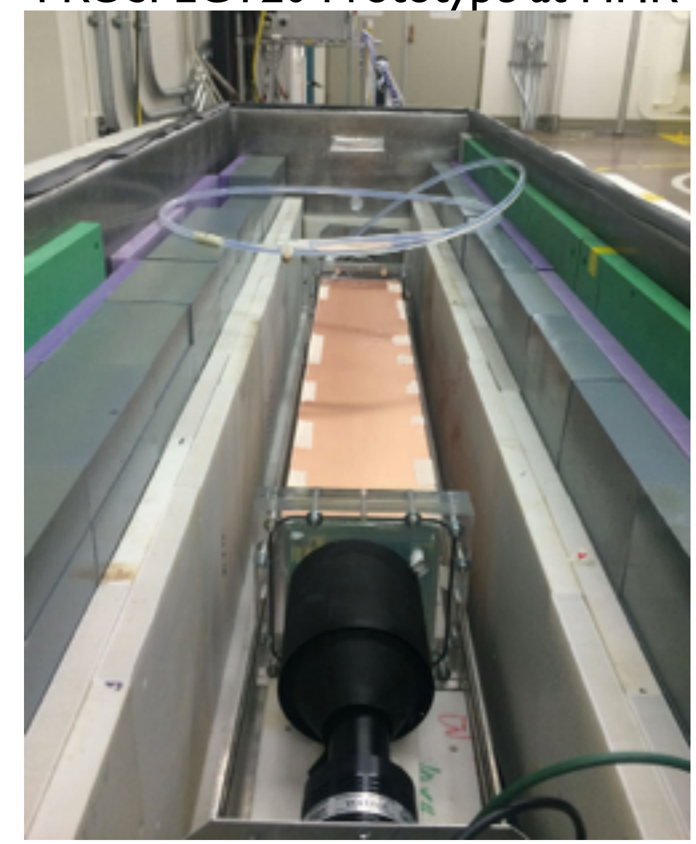
Illinois Institute of Technology

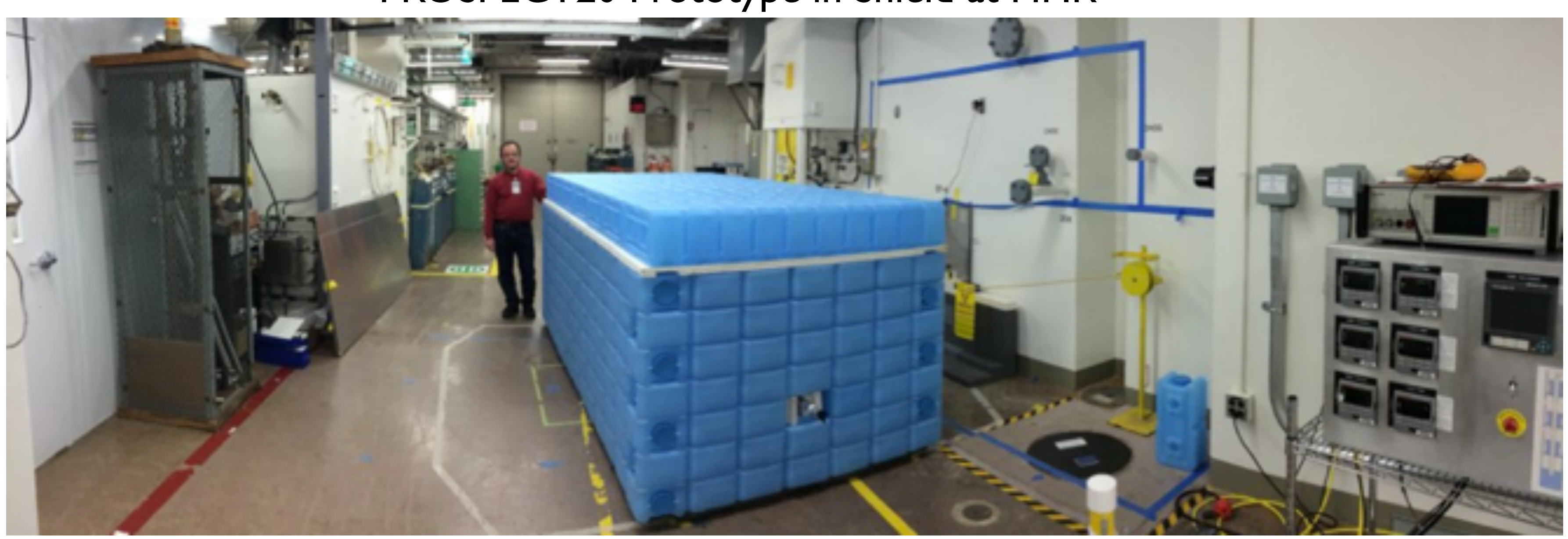
Daya Bay Antineutrino Spectrum



PROSPECT20 Prototype at HFIR



PROSPECT20 Prototype in Shield at HFIR



Outline

- Intro: Reactor $\overline{\nu}_e$ Flux and Spectrum Predictions
- Reactor Anomaly and recent flux/spectrum measurements
- Measurement of the $\overline{\nu}_e$ spectrum at PROSPECT
- Current context for PROSPECT

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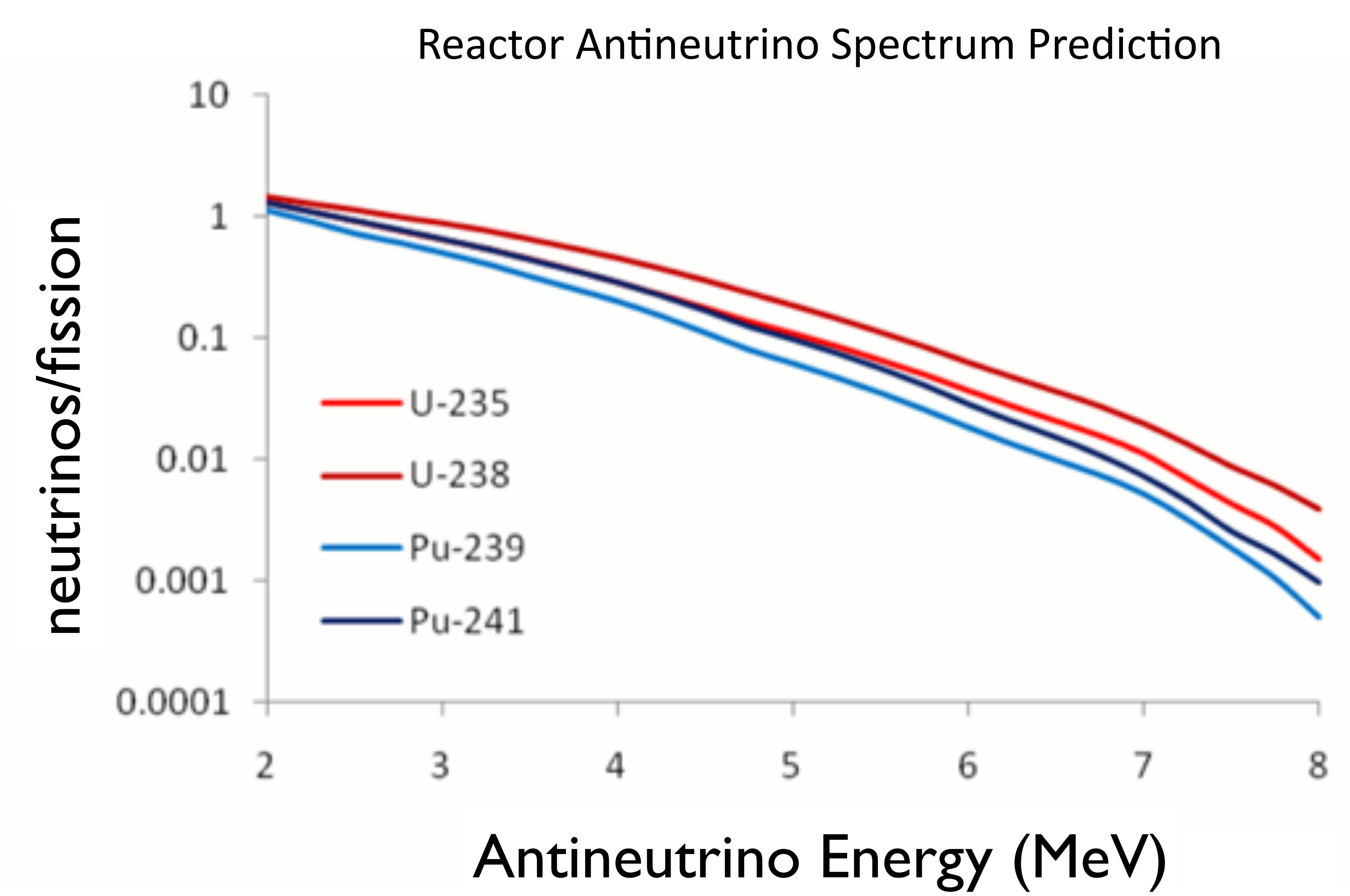
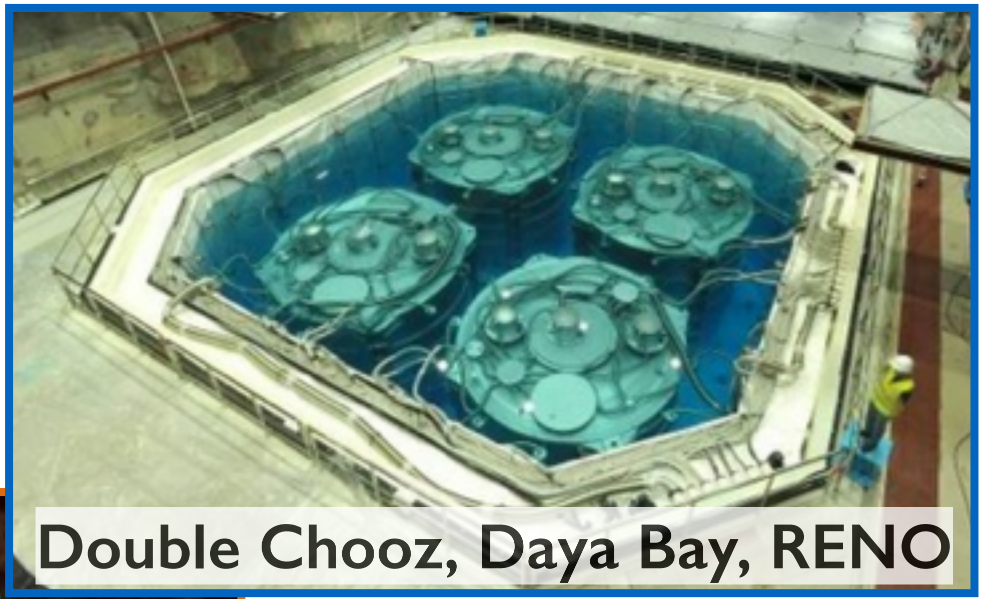


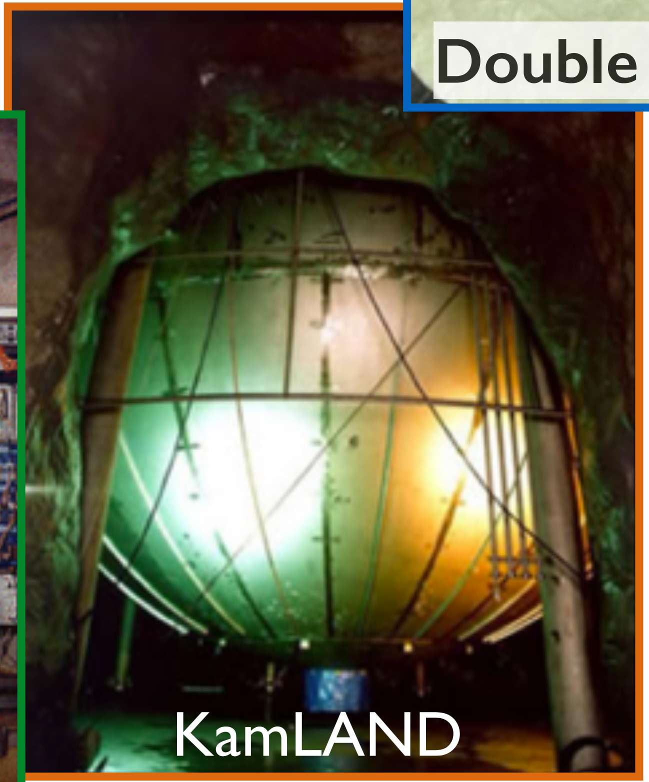
Reactor Neutrino History

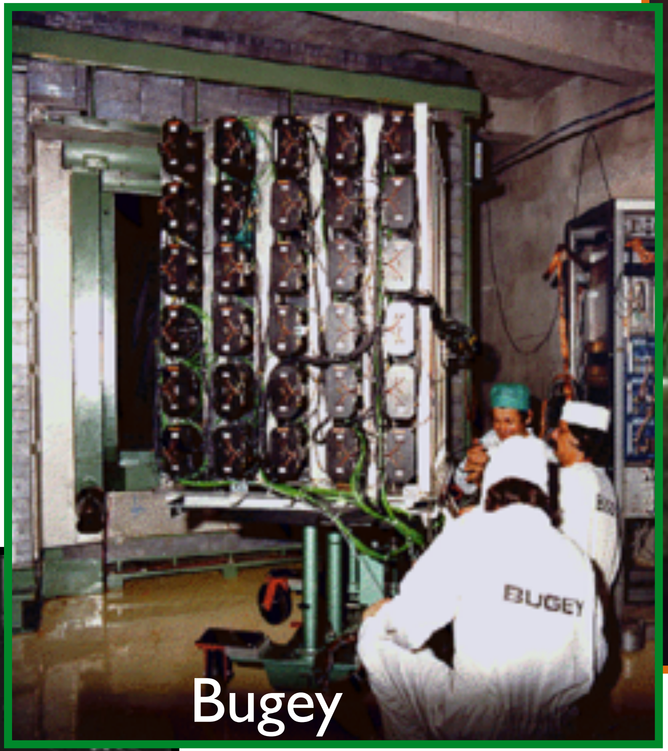
- Reactor $\bar{\nu}_e$: a history of discovery
  Many experiments, differing baselines



1970s-80s-90s:
Reactor flux,
Cross-section measurements

2010s:
θ_{13}, precision oscillation measurements





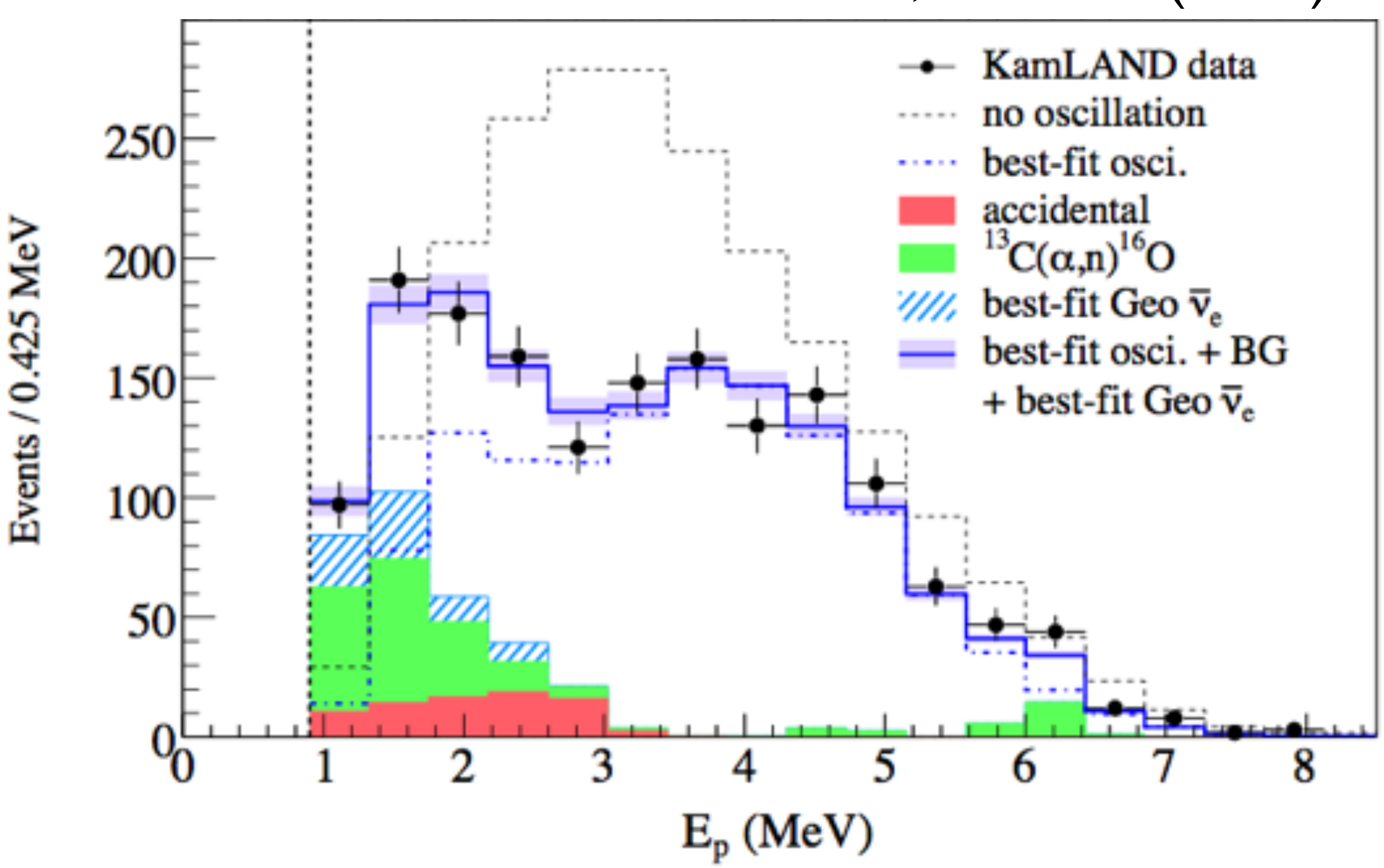
1950s: First neutrino observation

2000s: $\bar{\nu}_e$ disappearance,
$\bar{\nu}_e$ oscillation measurements

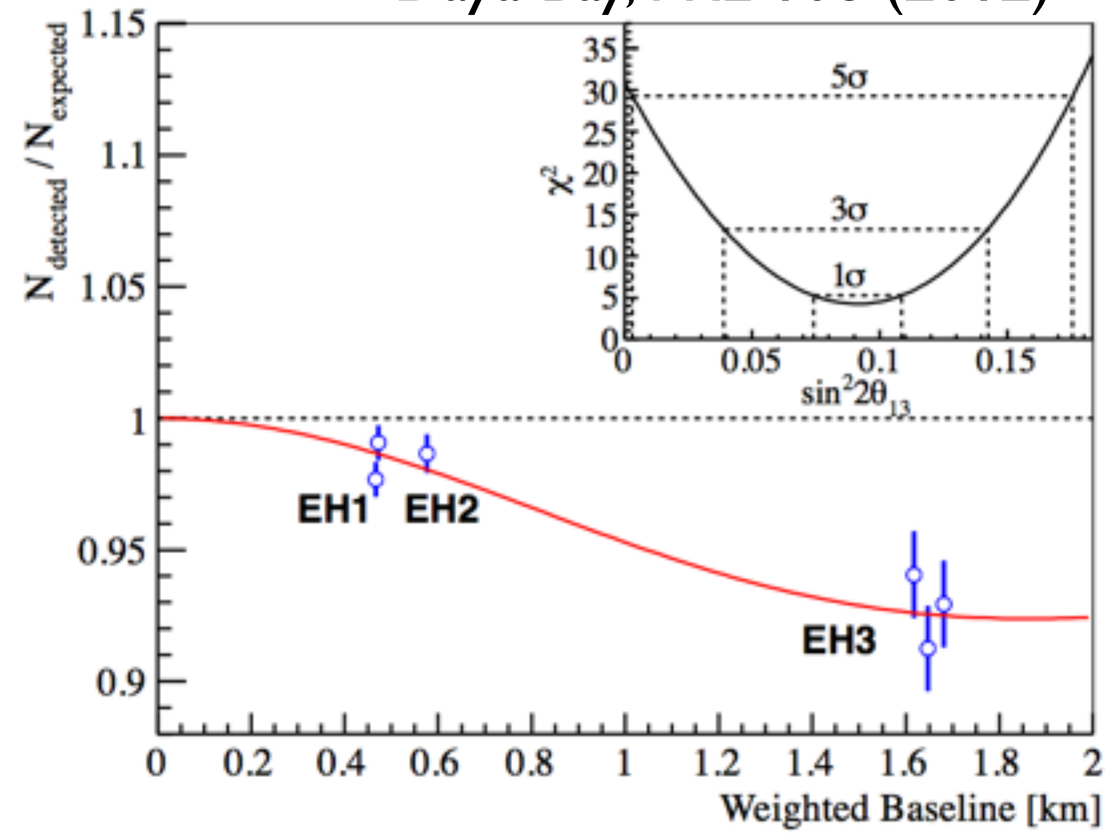
Reactor Neutrino Discovery

- How are these discoveries made?
- Comparing observed reactor neutrinos at different sites
- Comparing observed reactor neutrinos to predictions based on some model of how nuclear reactors work

KamLAND, PRL 100 (2008)



Daya Bay, PRL 108 (2012)



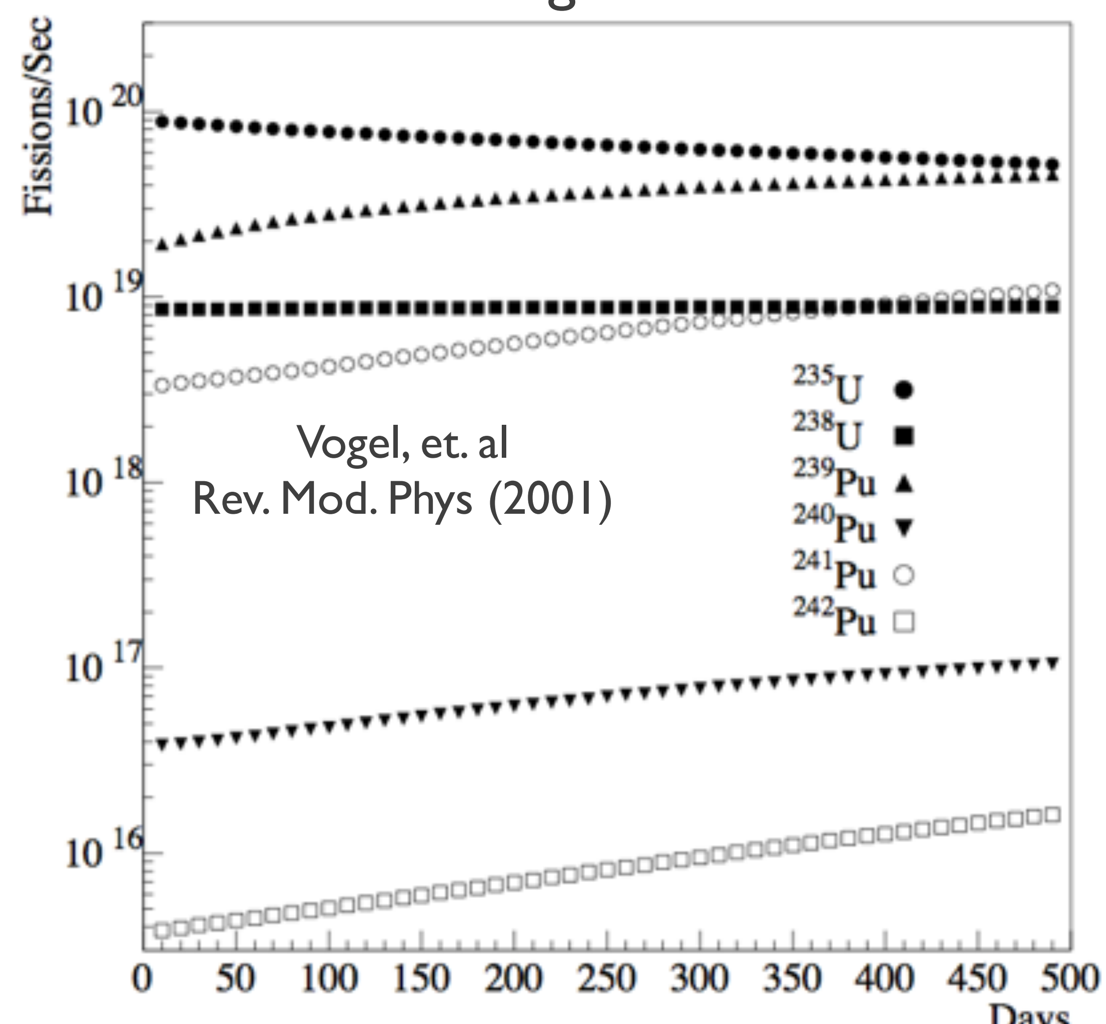
2000s: $\bar{\nu}_e$ disappearance, $\bar{\nu}_e$ oscillation measurements

2010s: θ_{13}, precision oscillation measurements

Reactor Antineutrino Production

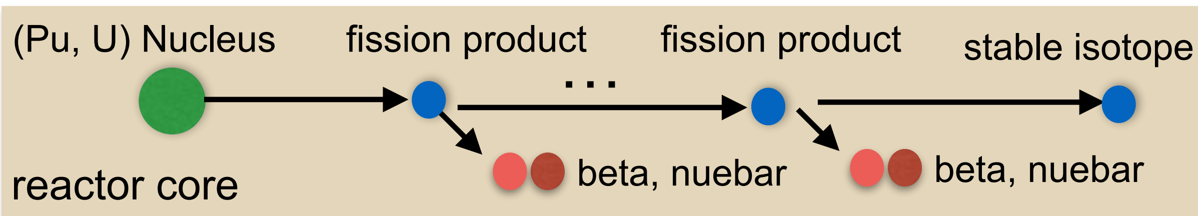
- Fission isotopes fission, creating neutron-rich daughters
  - Low-enriched (LEU): Many fission isotopes
  - Highly-enriched (HEU): U-235 fission only
- Overall fission rate described largely by reactor thermal power

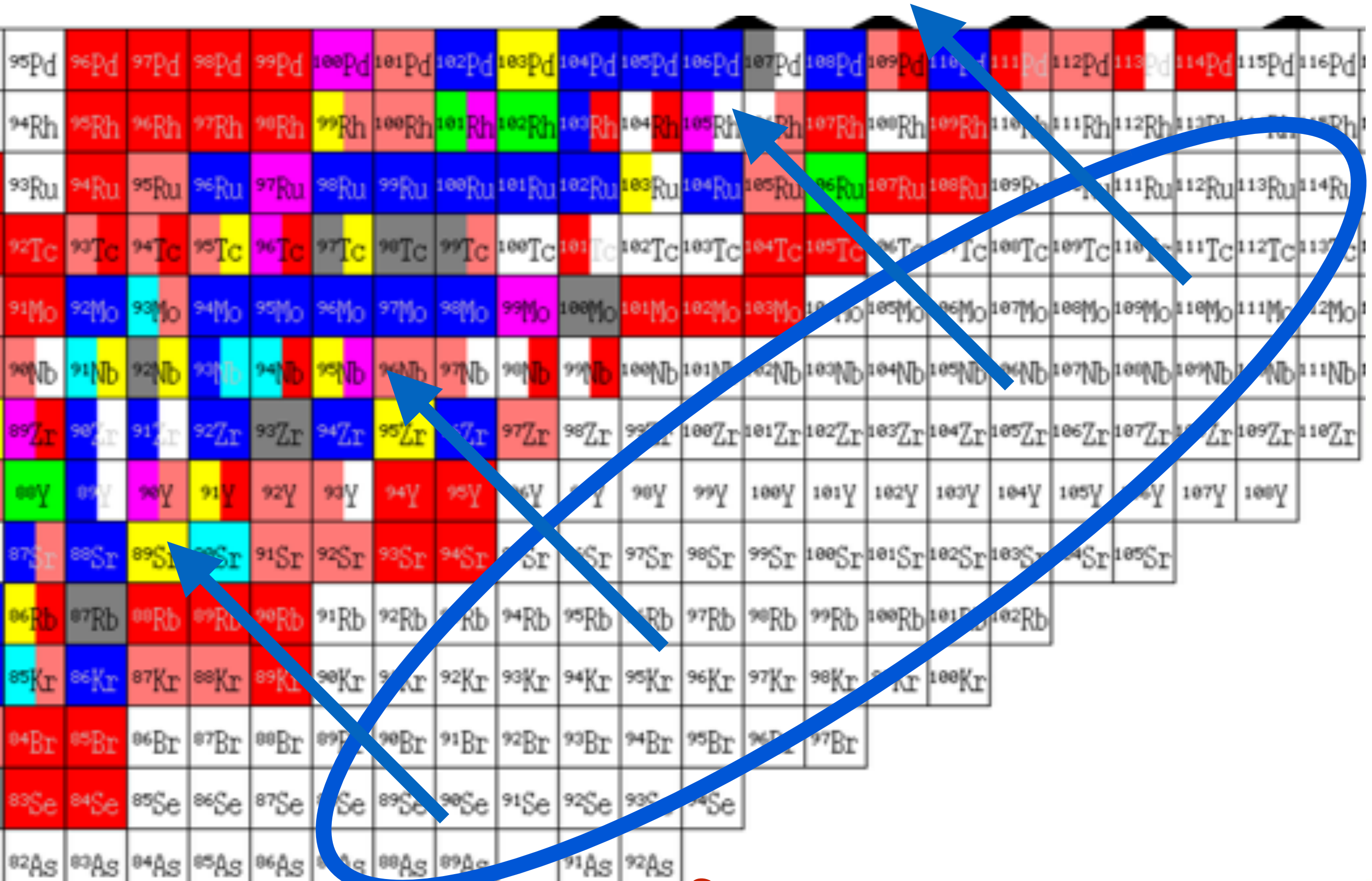
LEU Fission Fragment Contributors

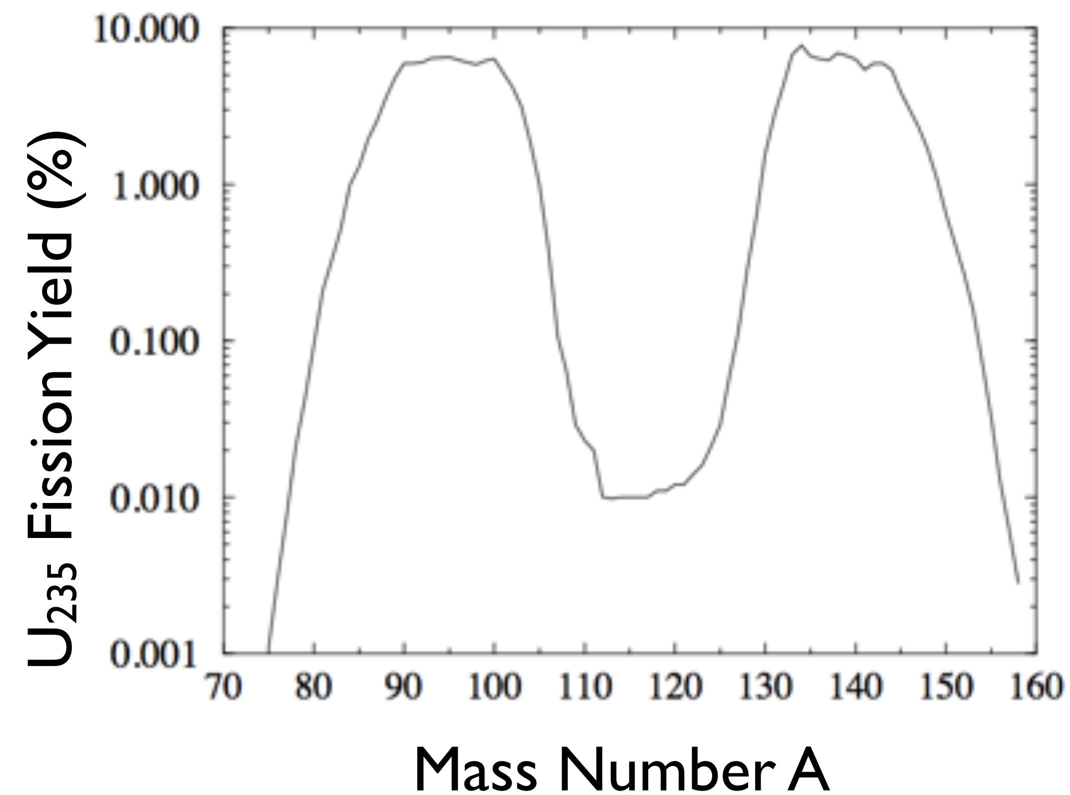


Reactor Antineutrino Production

- Reactor $\bar{\nu}e$: produced in decay of product beta branches
  - Each isotope: different branches, so different neutrino energies (slightly)



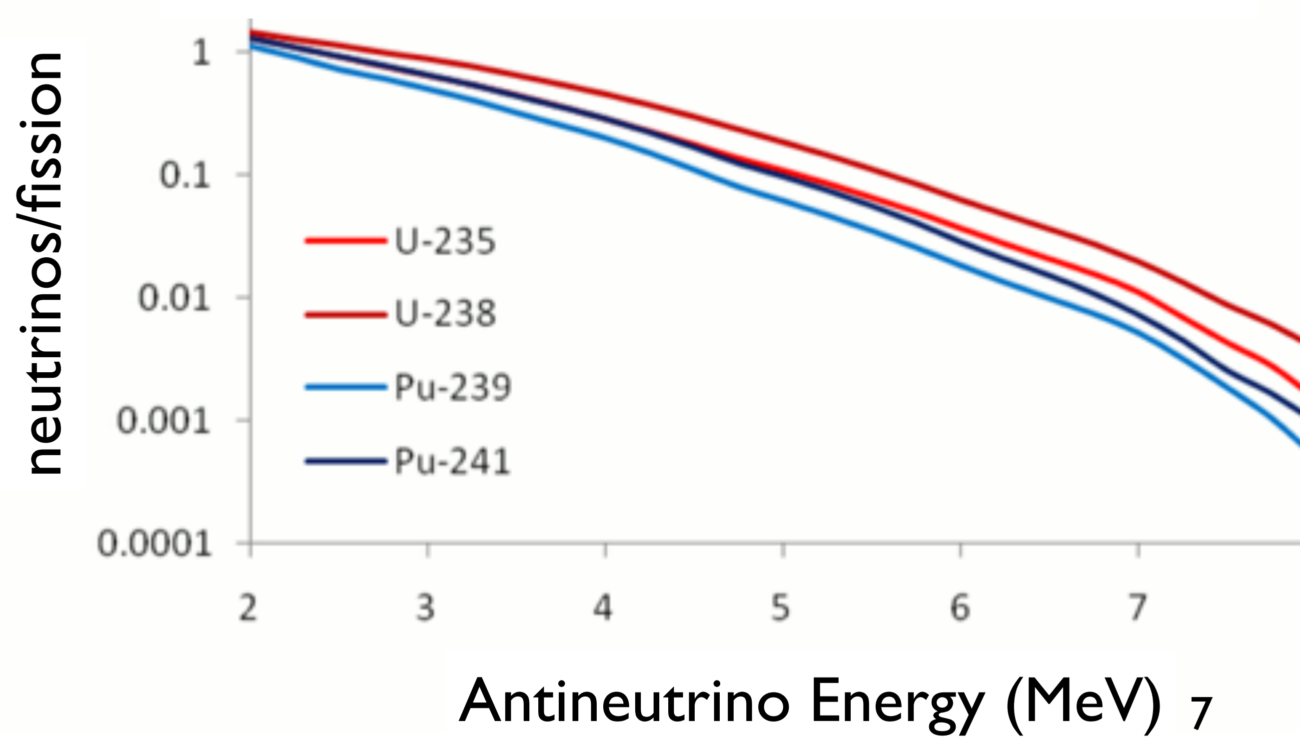




Spectrum

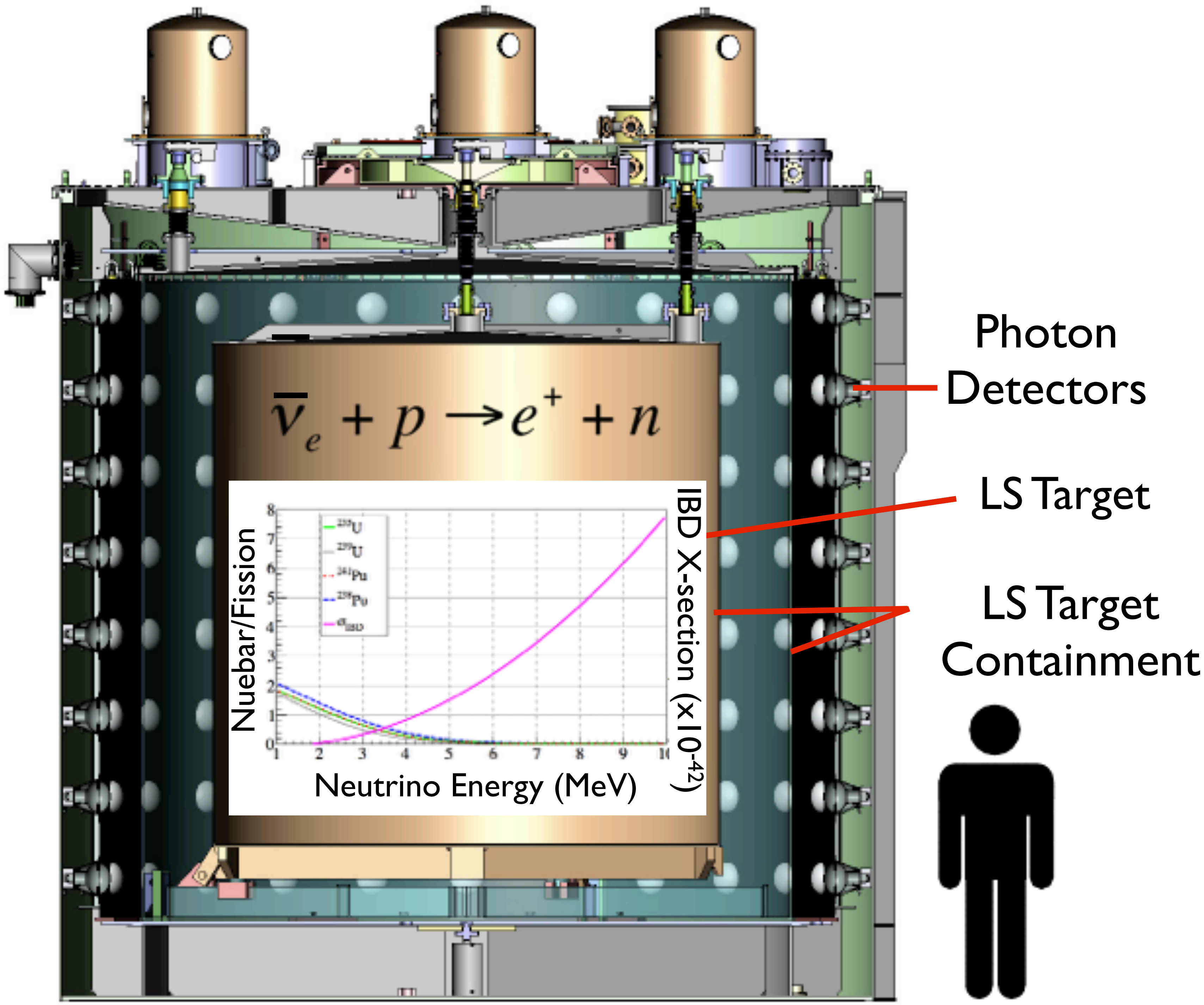
$$S(E) = \sum_{\boxed{i}} \boxed{F_i}\,\boxed{S_i(E)} \qquad F_i = \frac{W_{\mathrm{th}} f_i}{\sum_k f_k E_k}$$

Fission Isotope Flux

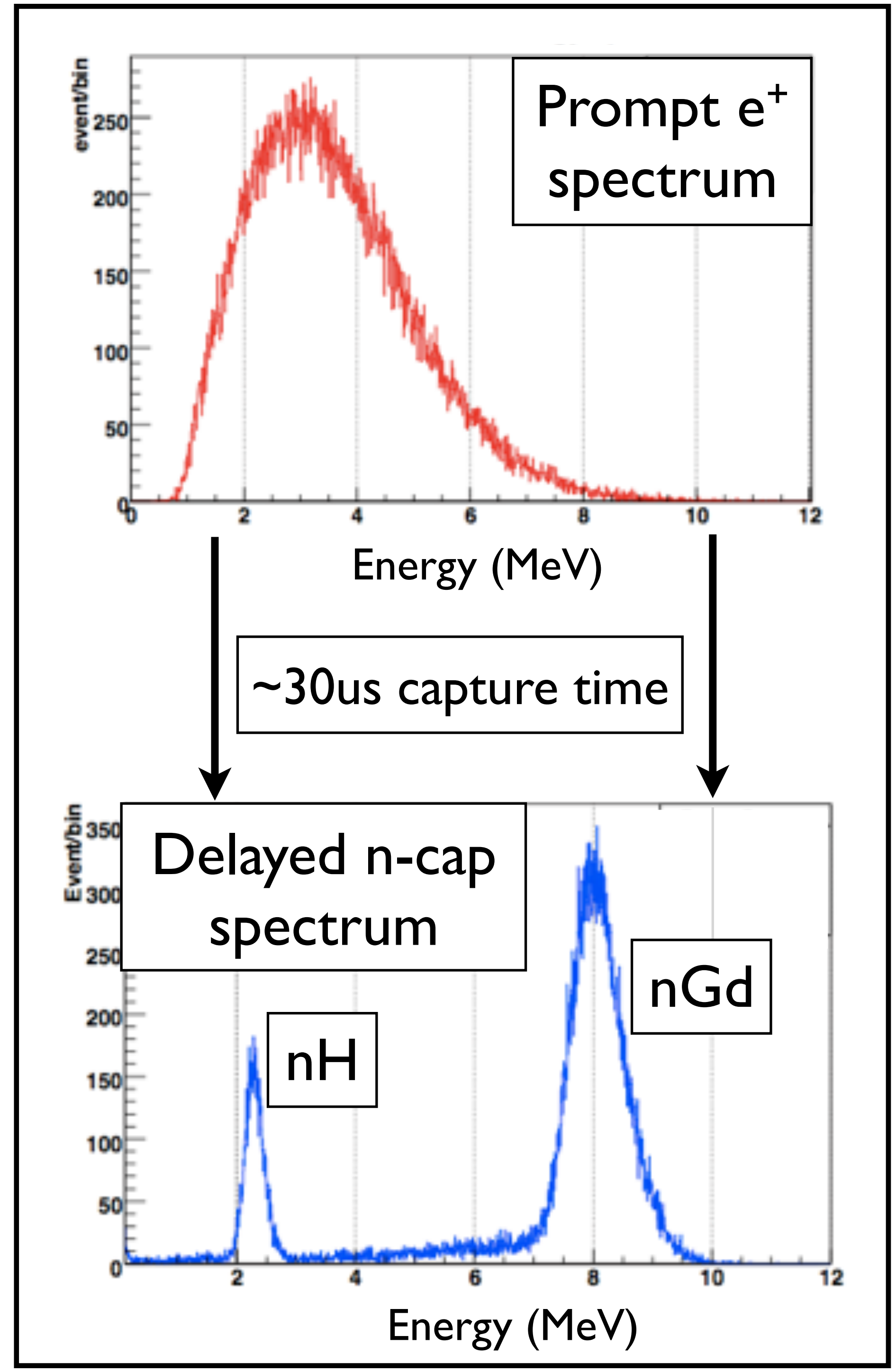


Reactor Antineutrino Detection

- Detect inverse beta decay with liquid or solid scintillator, PMTs
  - IBD e+ is direct proxy for antineutrino energy



Example: Daya Bay Detector



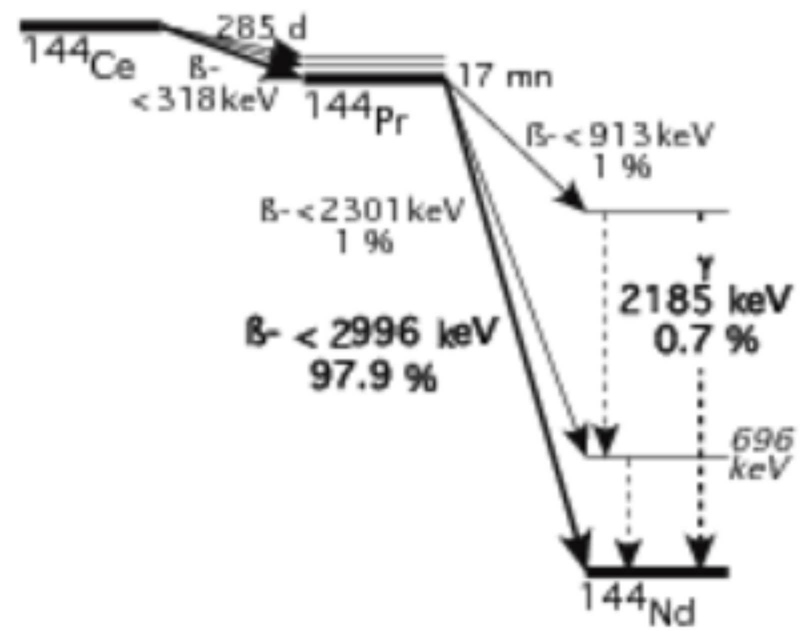
Daya Bay Monte Carlo Data

Predicting $S_i(E)$, Neutrinos Per Fission

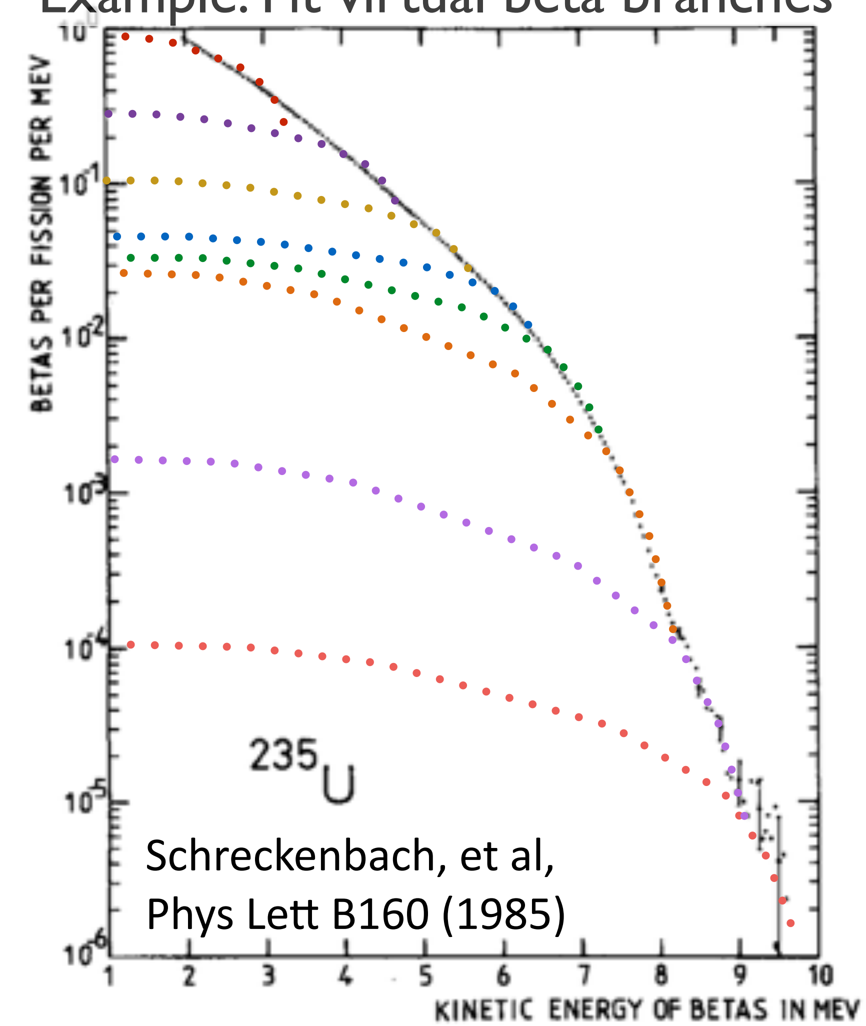
- Two main methods:
- *Ab Initio* approach:
  - Calculate spectrum branch-by-branch using beta branch databases: endpoints, decay schemes
  - **Problem:** many rare beta branches with little information; infer these additions
- Conversion approach
  - Measure beta spectra directly
  - Convert to $\overline{\nu}_e$ using 'virtual beta branches'
  - **Problem:** 'Virtual' spectra not well-defined: what forbiddenness, charge, etc. should they have?
- Devised in 50's, each method has lost and gained favor over the years

Carter, *et al*, Phys. Rev. 113 (1959)
King and Perkins, Phys. Rev. 113 (1958)

Example: Ce-144 Decay Scheme



Example: Fit virtual beta branches



Predicting $S_i(E)$, Neutrinos Per Fission

- Early 80s: ILL $\bar{\nu}_e$ data fits newest *ab initio* spectra well

  Davis, Vogel, *et al.*, **PRC** 24 (1979)
  Kown, et al., **PRD** 24 (1981)

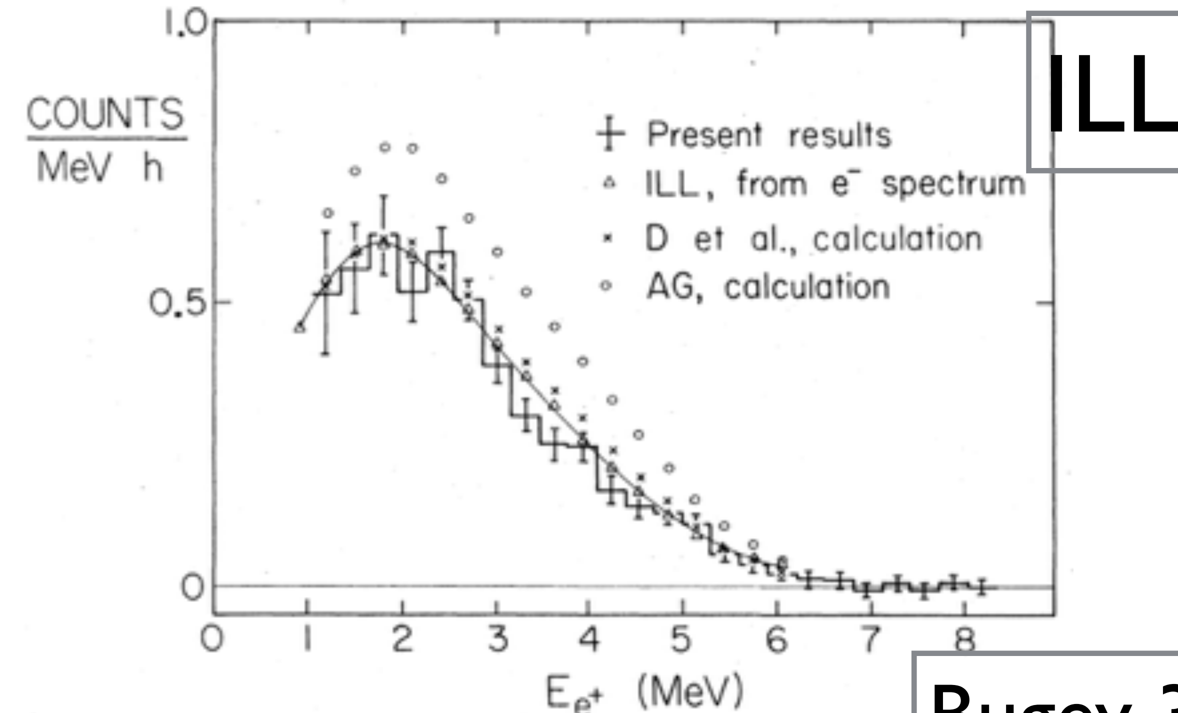
- 1980s: New reactor beta spectra: measurements — conversion now provides lower systematics

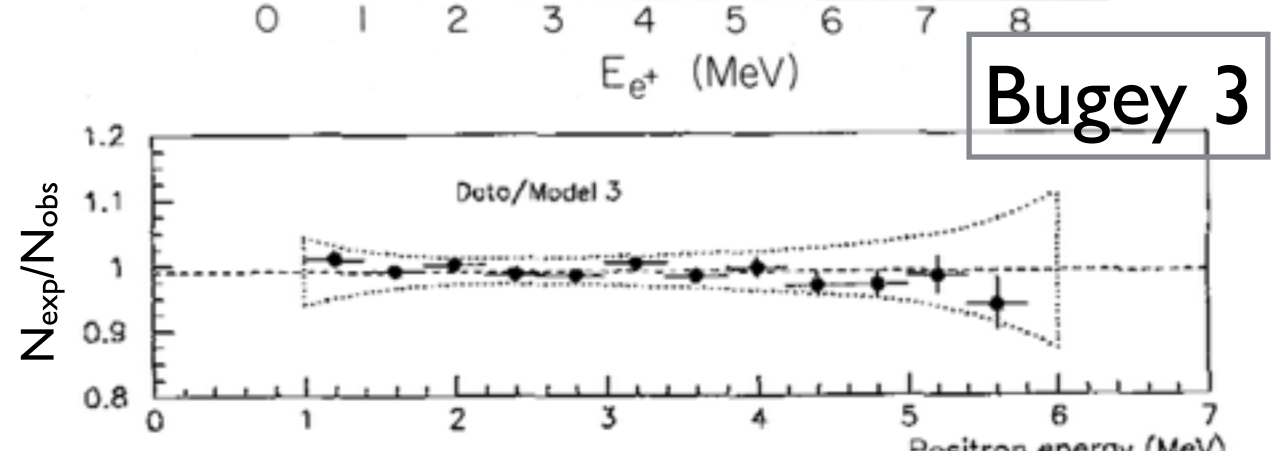
  Schreckenbach, *et al.*, Phys Lett **B**160 (1985)
  Schreckenbach, *et al.*, Phys Lett **B**218 (1989)

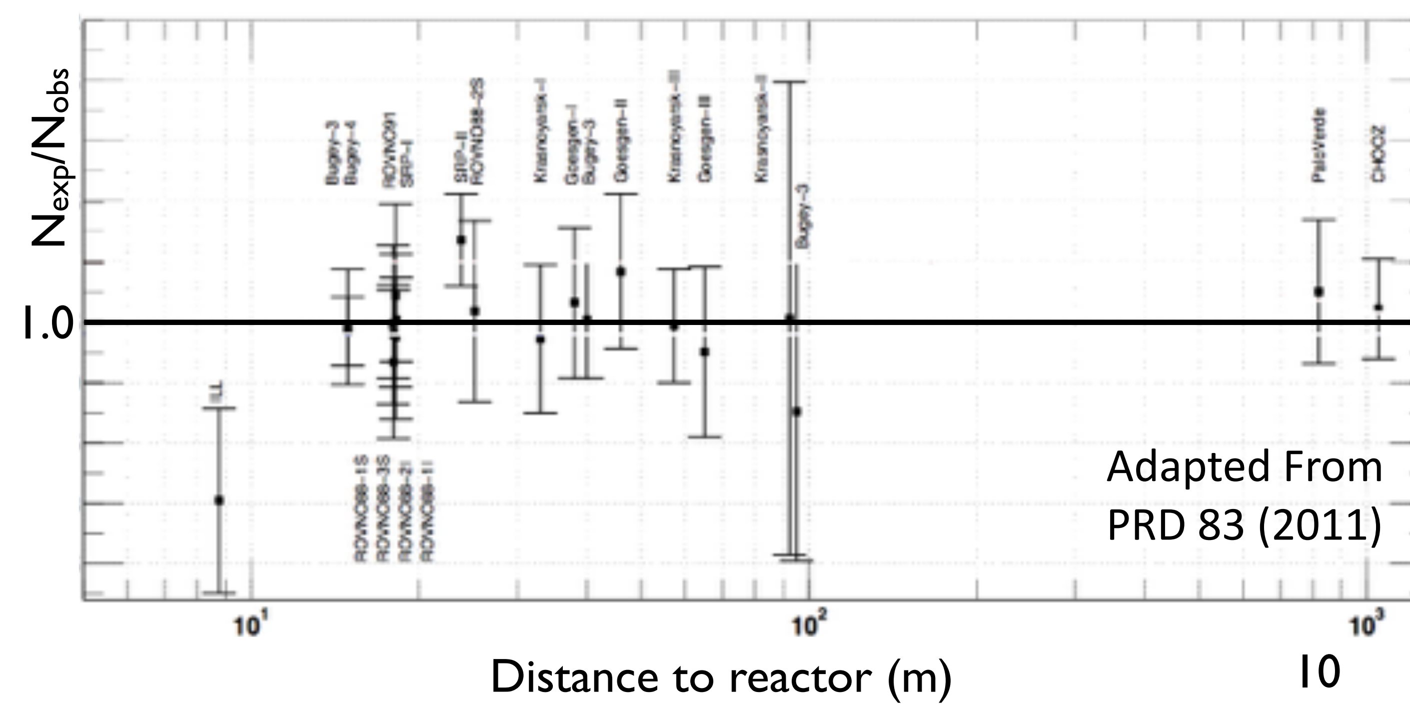
- 1990s: Bugey measurements fit converted spectrum well

  B. Achkar, *et al.*, Phys Lett B374 (1996)

- 1980s-2000s: Predicted, measured fluxes agree





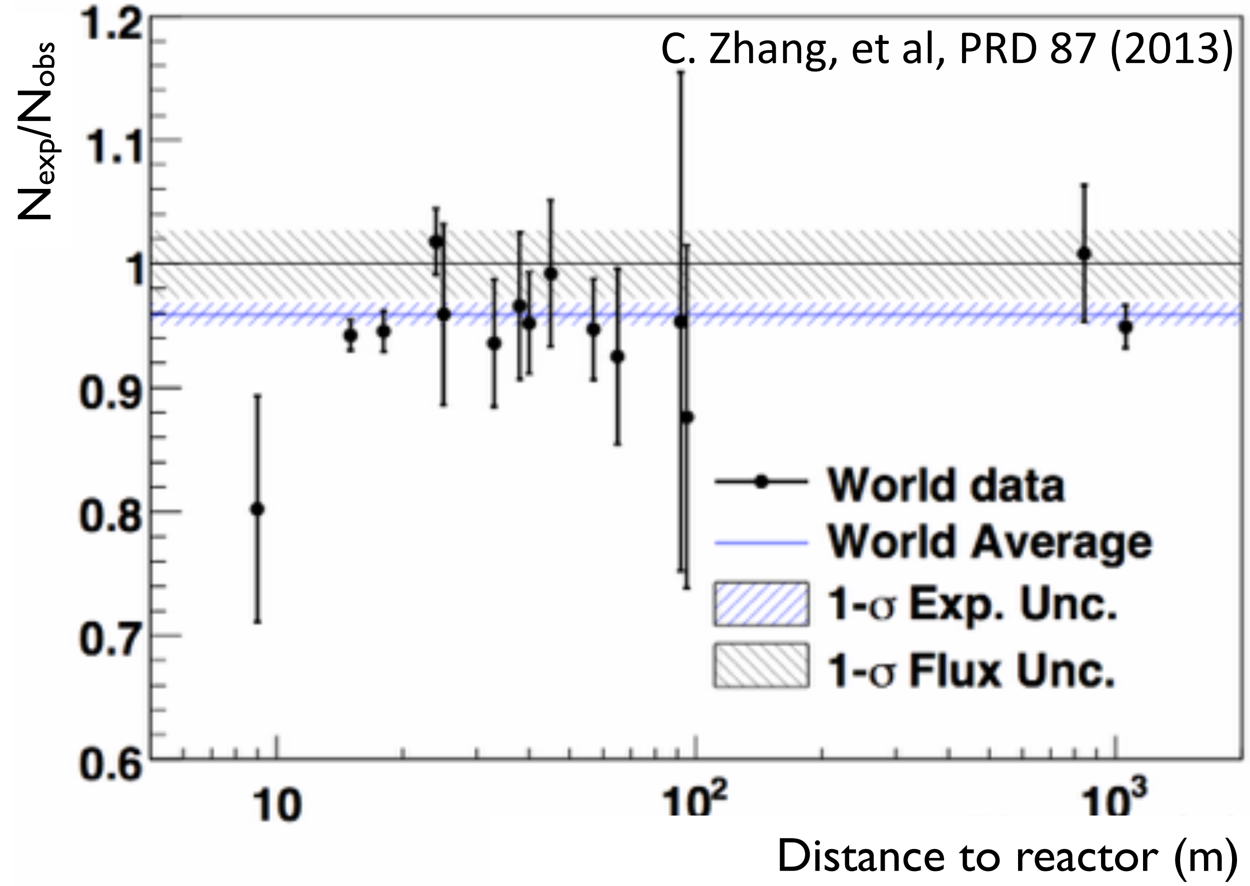


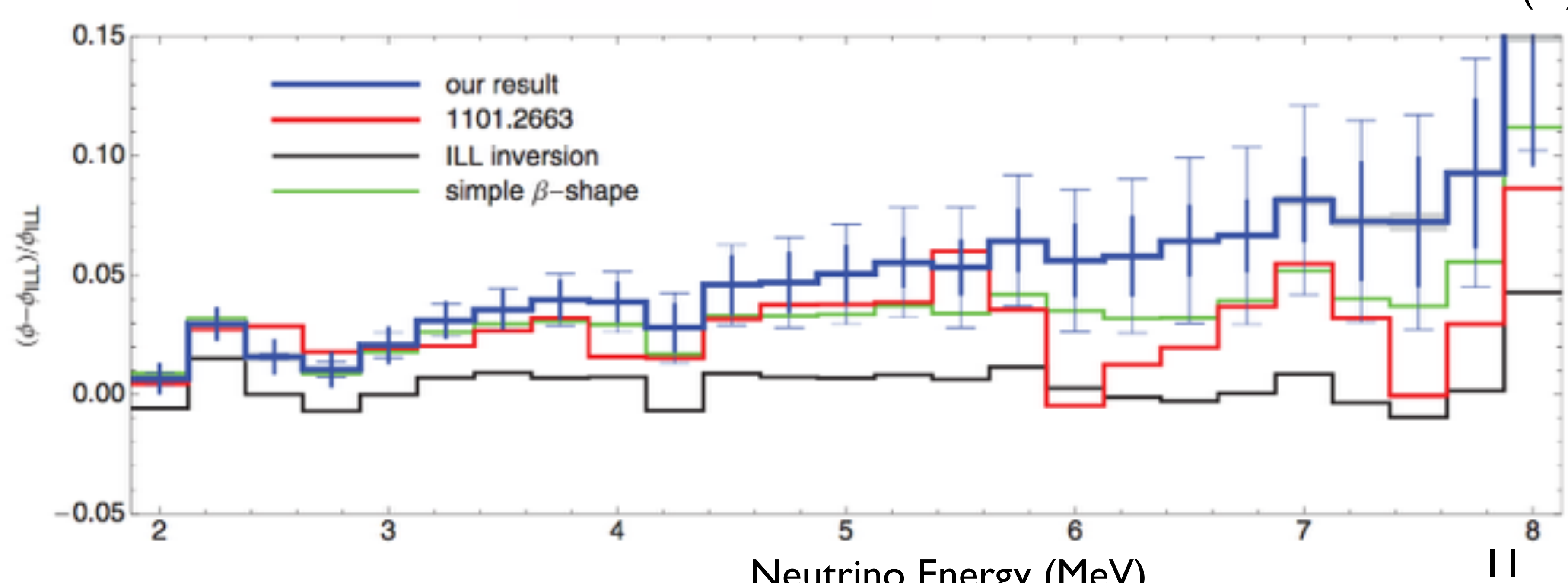
Adapted From PRD 83 (2011)

Recent History: Problems Emerge

- 2010s: Re-calculation of conversion for θ_{13} measurements
  - Start with ab initio approach
  - Subtract this from ILL beta spectra
  - Use conversion procedure on remaining beta spectrum: ~10%
  - OR Huber: virtual branches only
- Change in flux/spectrum!
  - Flux increase from:
    - Conversion (~3%)
    - X-section (1%)
    - Non-equilibrium isotopes (1%)

Mueller, *et al*, Phys. Rev. C83 (2011)
Mention, *et al*, Phys. Rev. D83 (2011)
Huber, Phys. Rev. C84 (2011)





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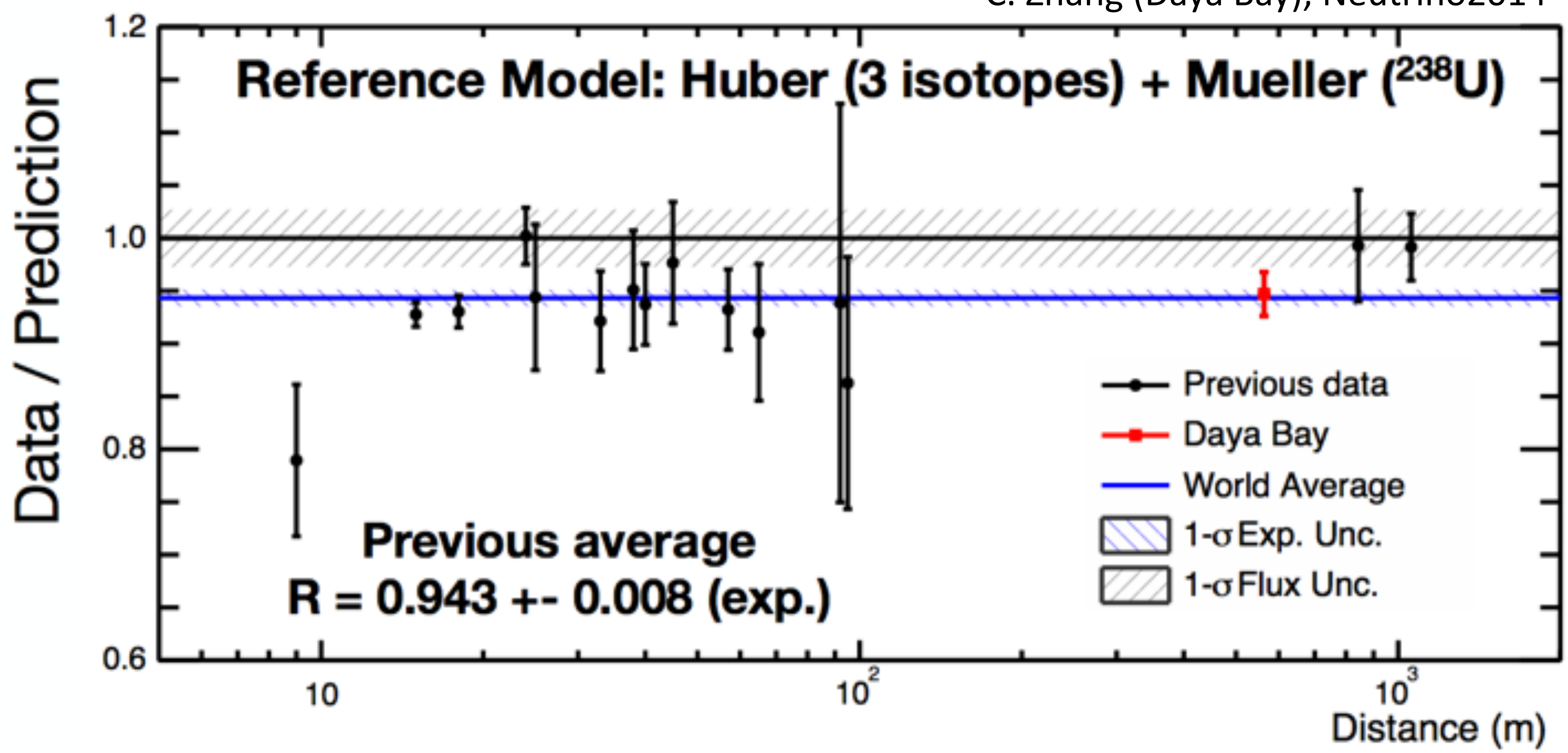
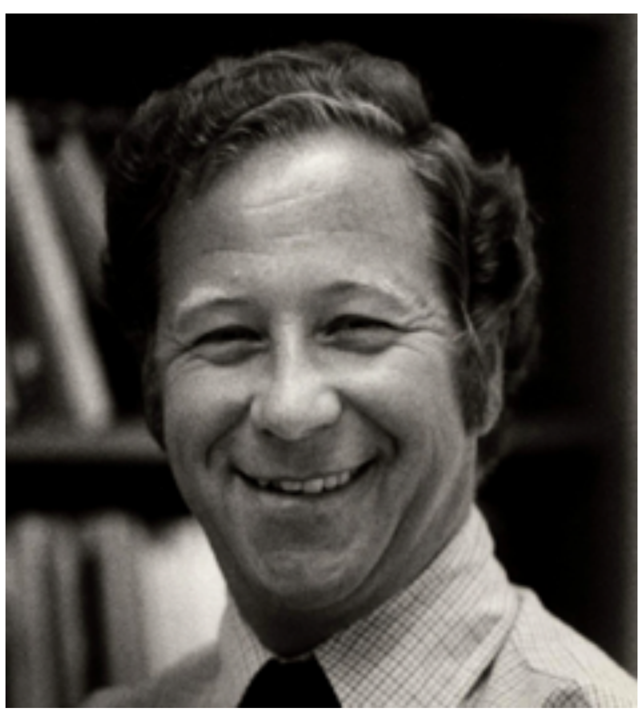
C. Zhang (Daya Bay), Neutrino2014



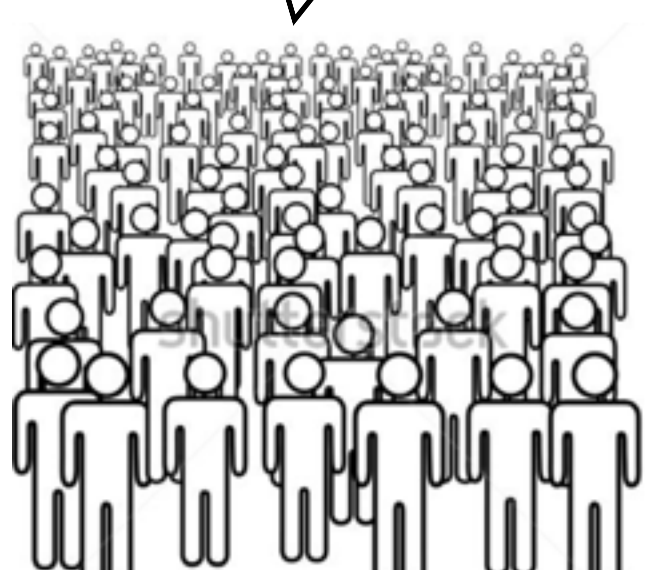
Reactor Antineutrino Anomaly?

- Do we have a ‘reactor antineutrino anomaly?’
  - “No: the previous experiments could have been biased to report flux measurements that agreed with existing predictions of the time.”
  - “Yes: but probably attributable to uncertainties in the beta-to-ν_e conversion.”
  - “Yes: the deficit could result from short-baseline sterile neutrino oscillations.”

???



P. Vogel, Caltech



The rest of us

T. Lasserre, CEA, France

P. Huber, VTech

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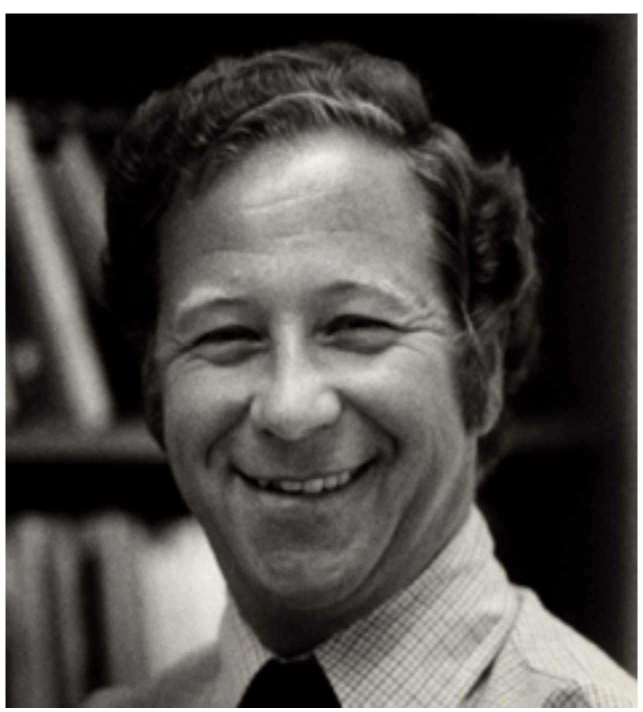
We need more data!!



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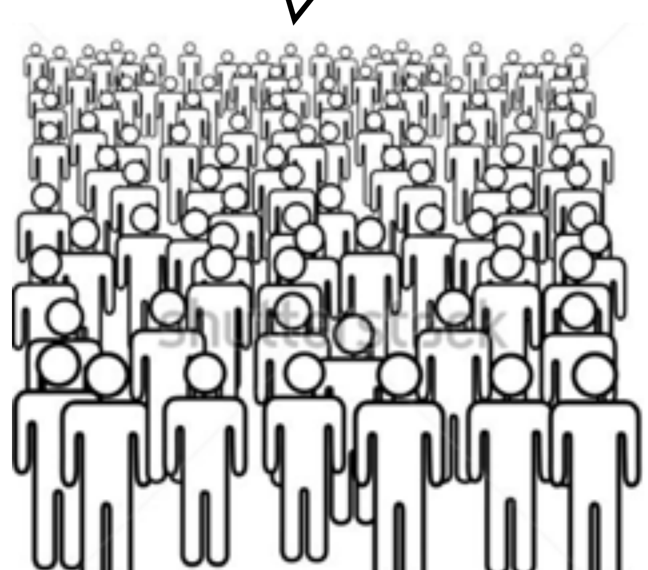

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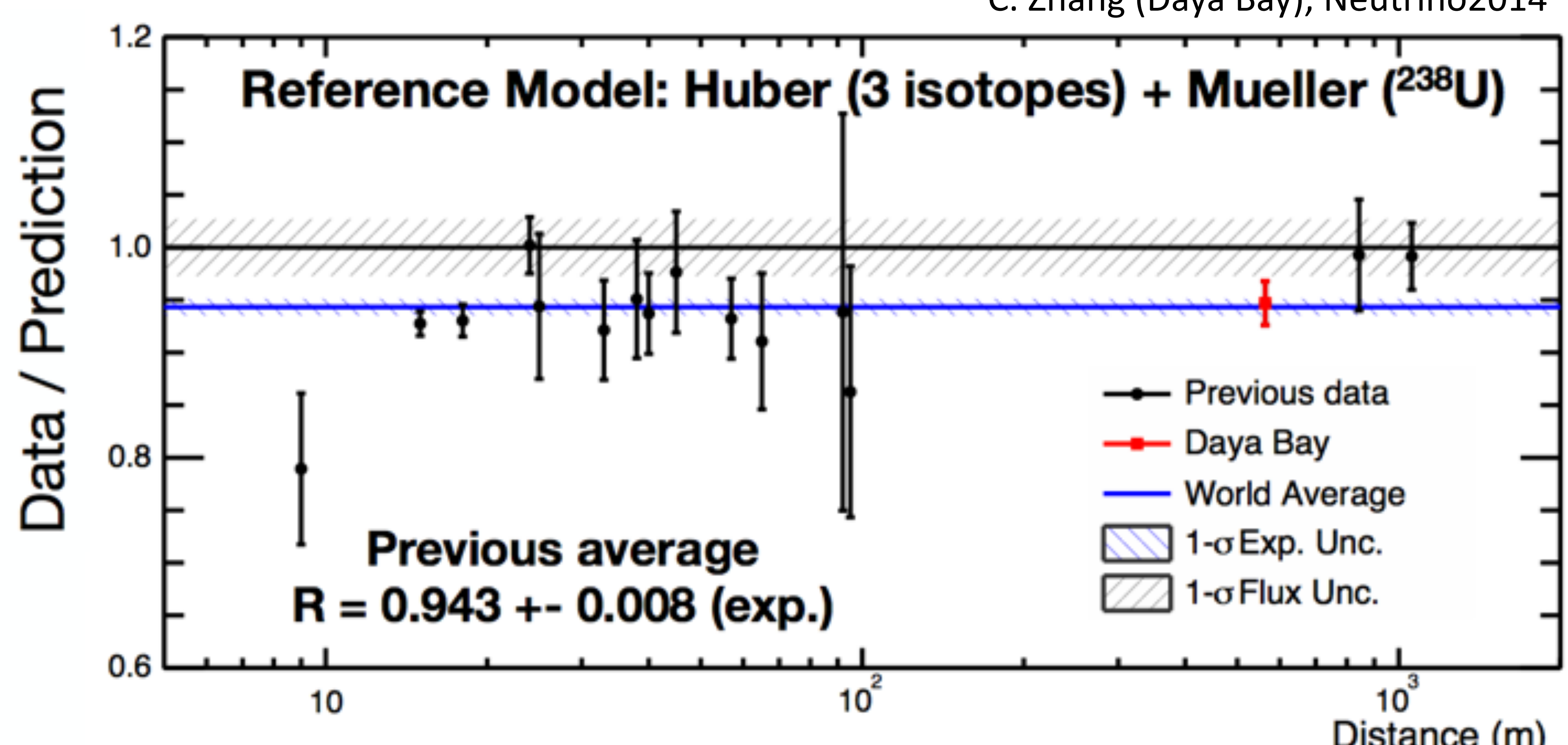
Reactor Anomaly Explanations

- Do we have a ‘reactor antineutrino anomaly?’
  - “No: the previous experiments could have been biased to report flux measurements that agreed with existing predictions of the time”
- Daya Bay also sees the reactor flux deficit
  - 5% deficit relative to 2011 Huber/Mueller flux prediction
  - Blind analysis: No reactor power data available until analysis is totally fixed

C. Zhang (Daya Bay), Neutrino2014

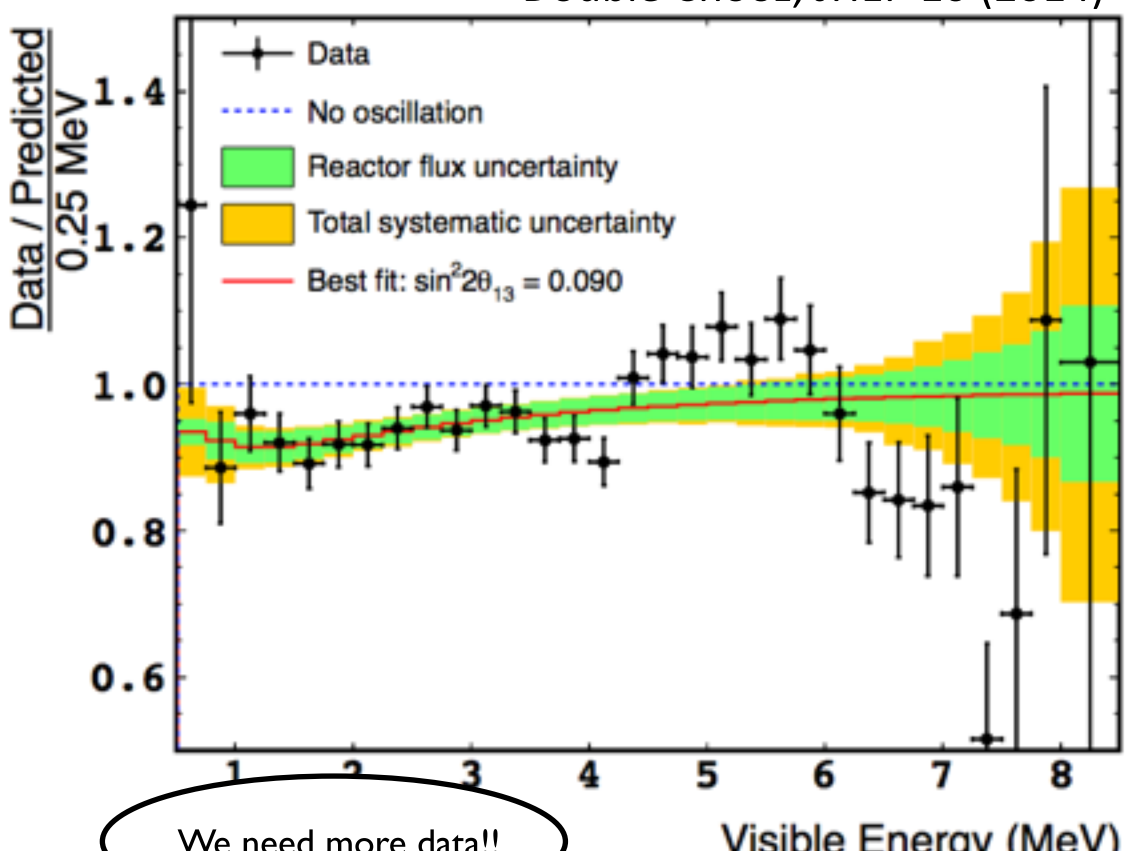


C. Zhang (Daya Bay)
Neutrino 2014

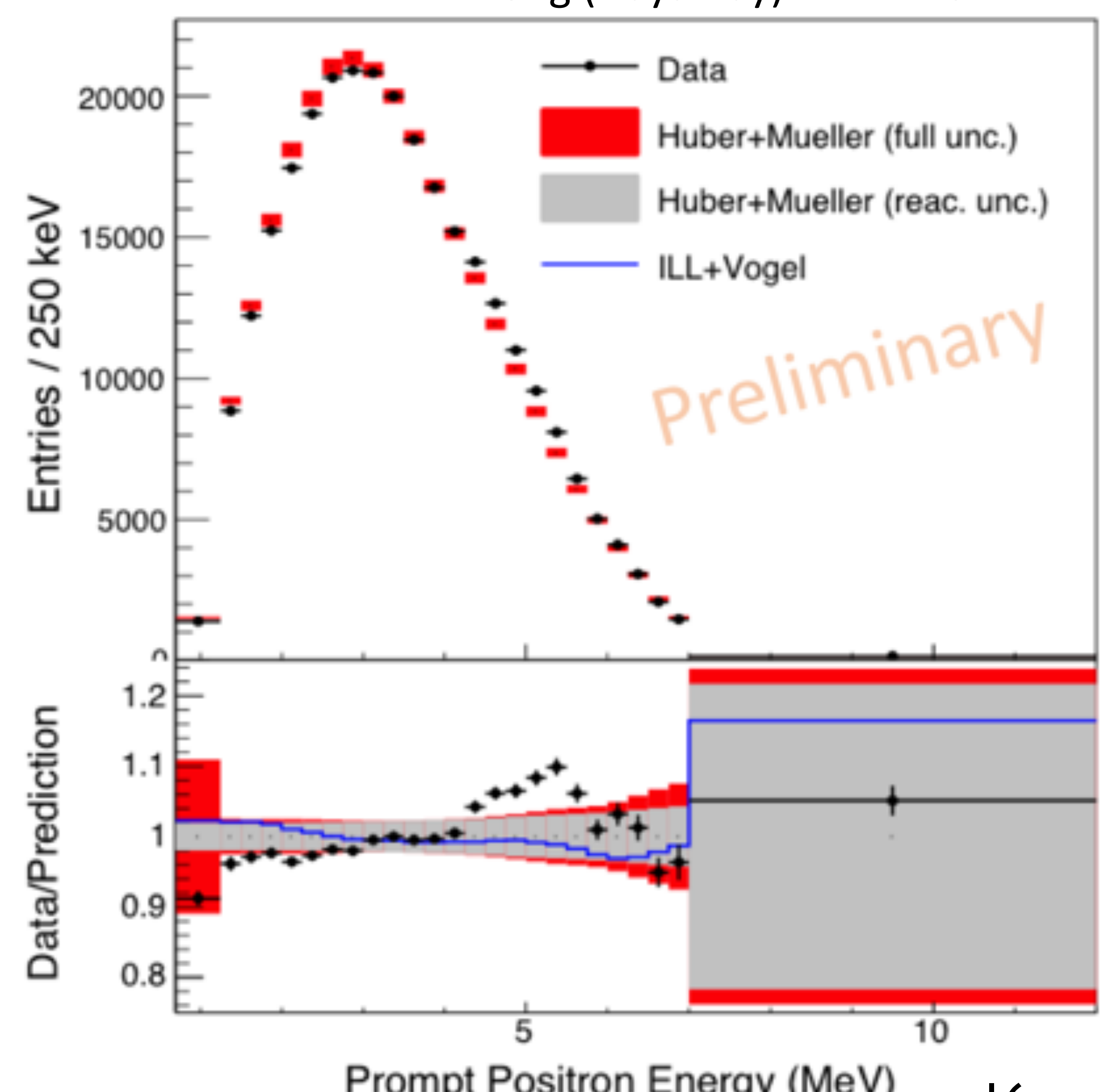
Reactor Anomaly Explanations

- Do we have a ‘reactor antineutrino anomaly?’
  - “Yes: it’s probably attributable to problems in the beta-to-ν_e conversion”
- Spectra from θ_{13} experiments disagree with predictions
  - “If measured spectrum doesn’t match, why should measured flux?”

Double Chooz, JHEP 10 (2014)



W. Zhong (Daya Bay) ICHEP 2014



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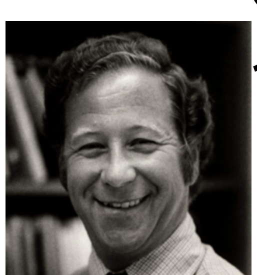
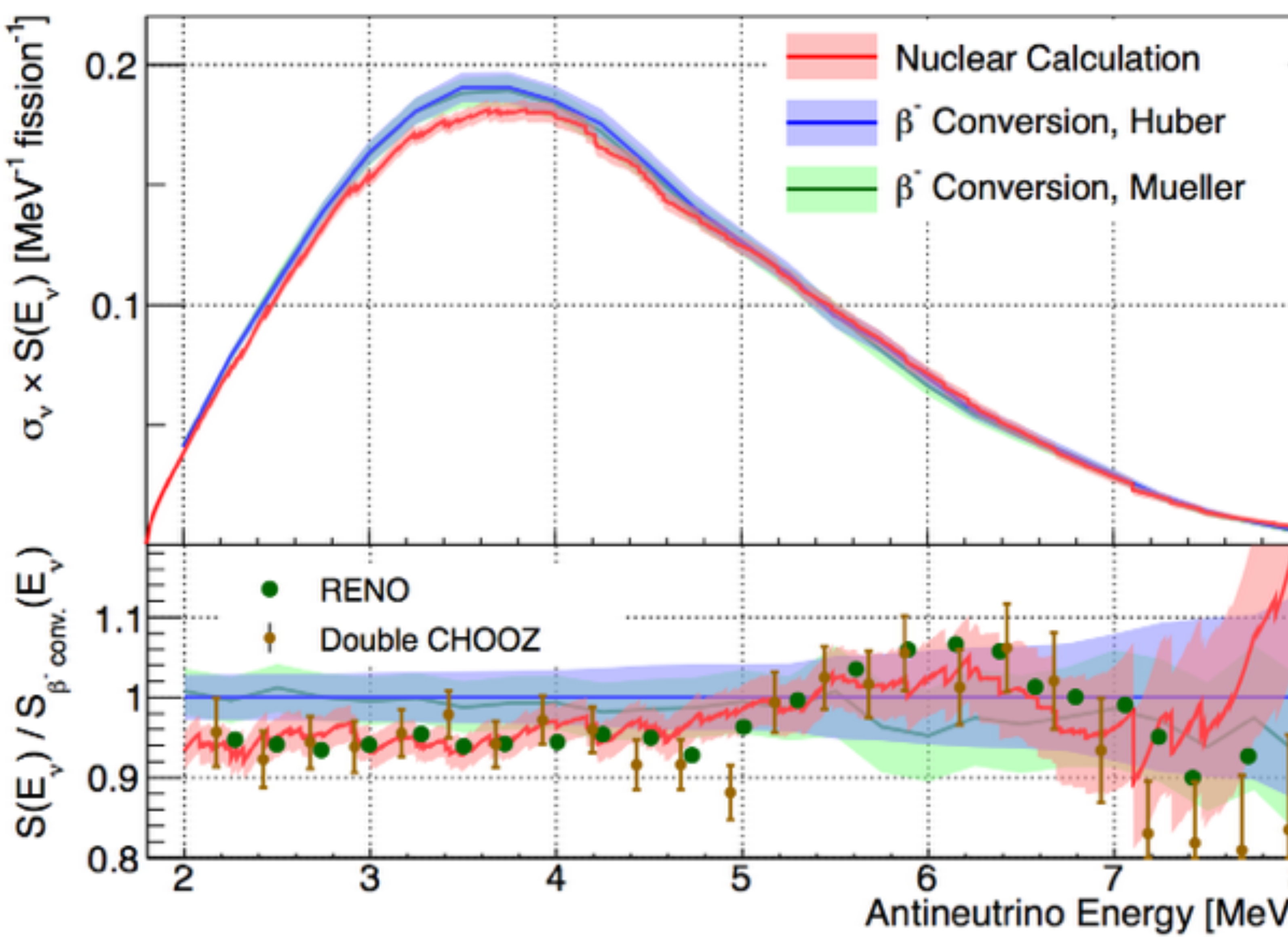


Reactor Anomaly Explanations

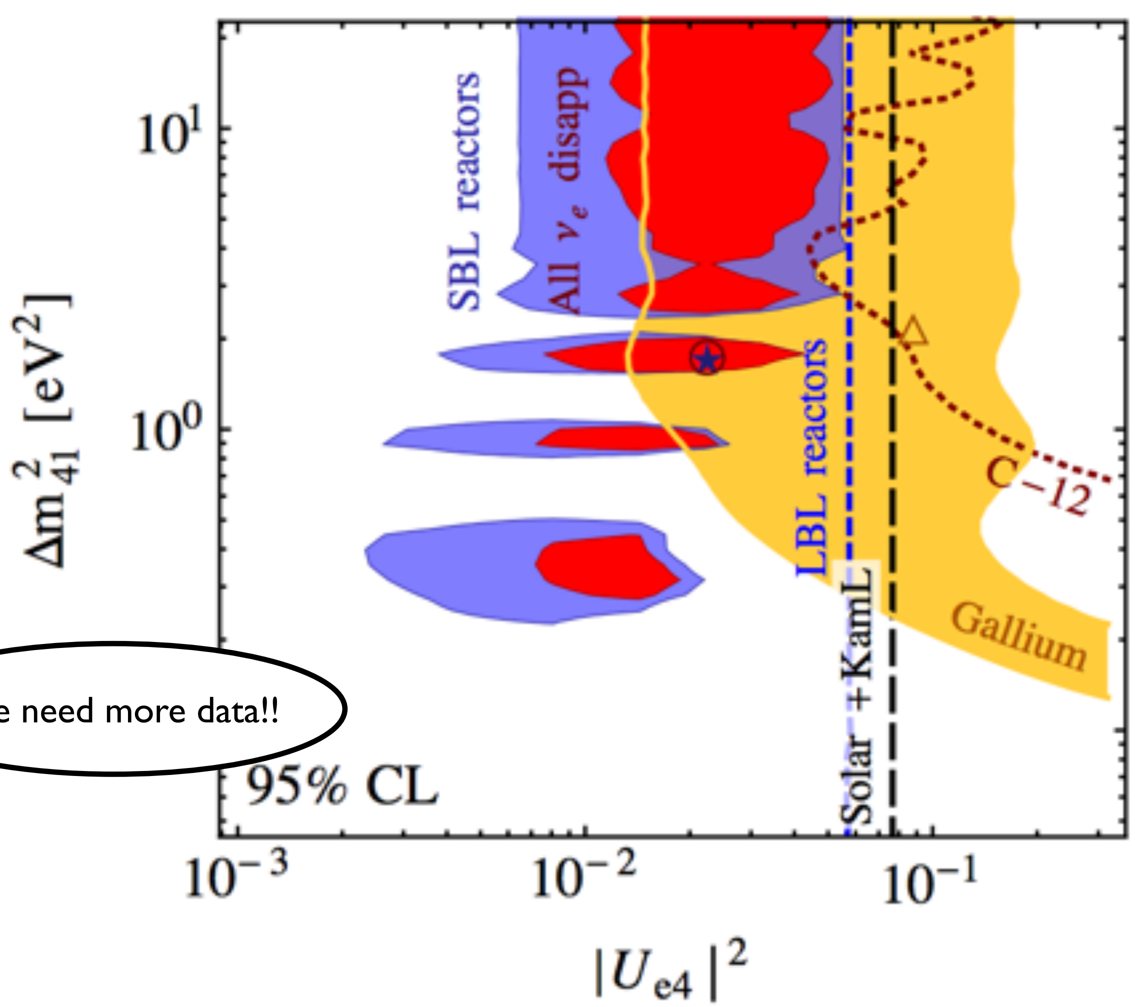
- Do we have a 'reactor antineutrino anomaly?'
  - "Yes: it's probably attributable to problems in the beta-to-ν_e conversion"
- New *ab initio* shape seems to match RENO/DC data quite well
  - But not the flux…?
  - Not enough data to constrain this situation further!

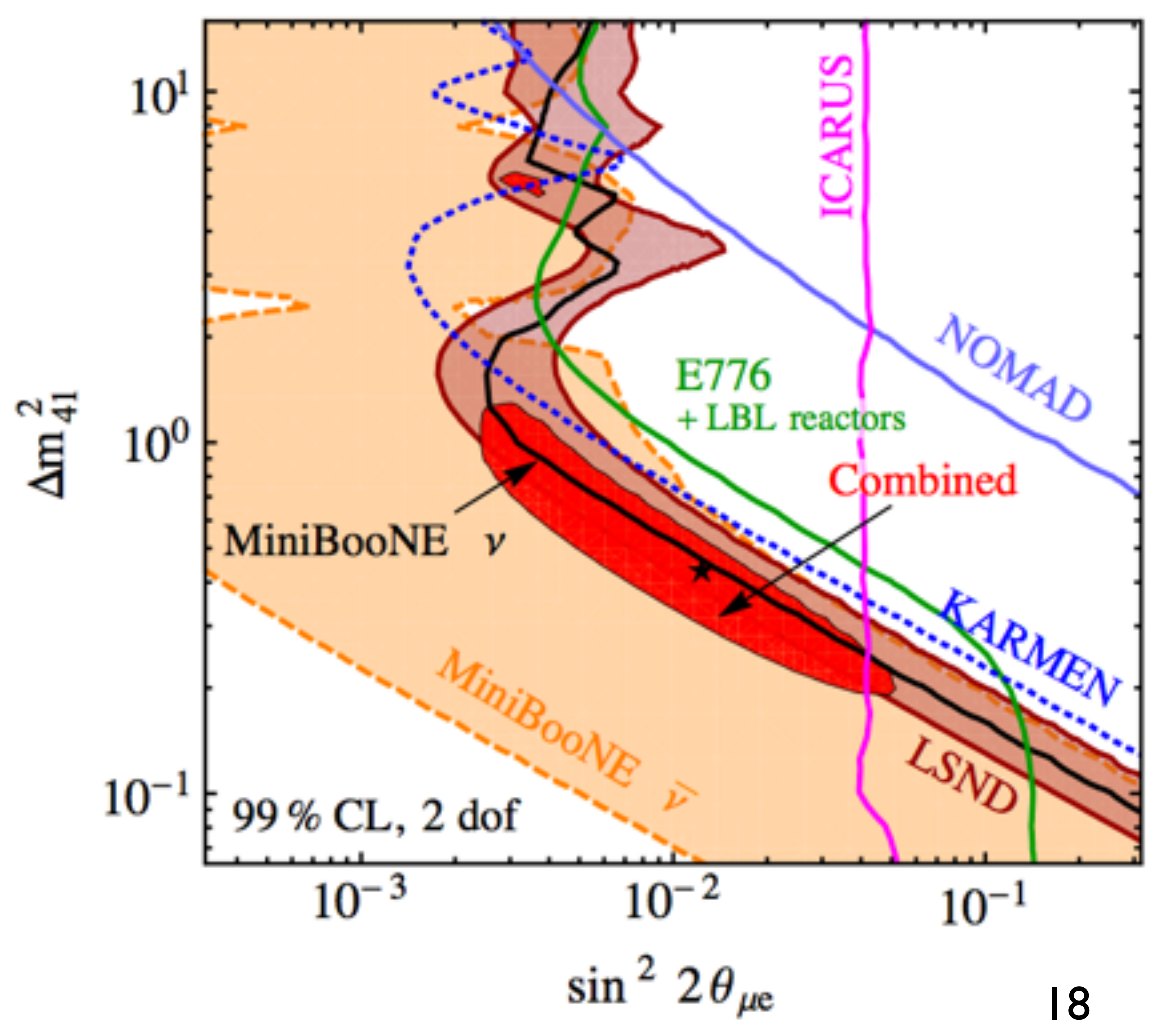
Dwyer and Langford, PRL 114 (2015)



Reactor Anomaly Explanations

- Do we have a ‘reactor antineutrino anomaly?’
  - “Yes: the deficit could result from short-baseline sterile neutrino oscillations”
- Consistent with existing nonzero hints for sterile neutrinos
  - LSND, MiniBooNE, Gallium
  - However, tension with null ν_μ disappearance measurements…





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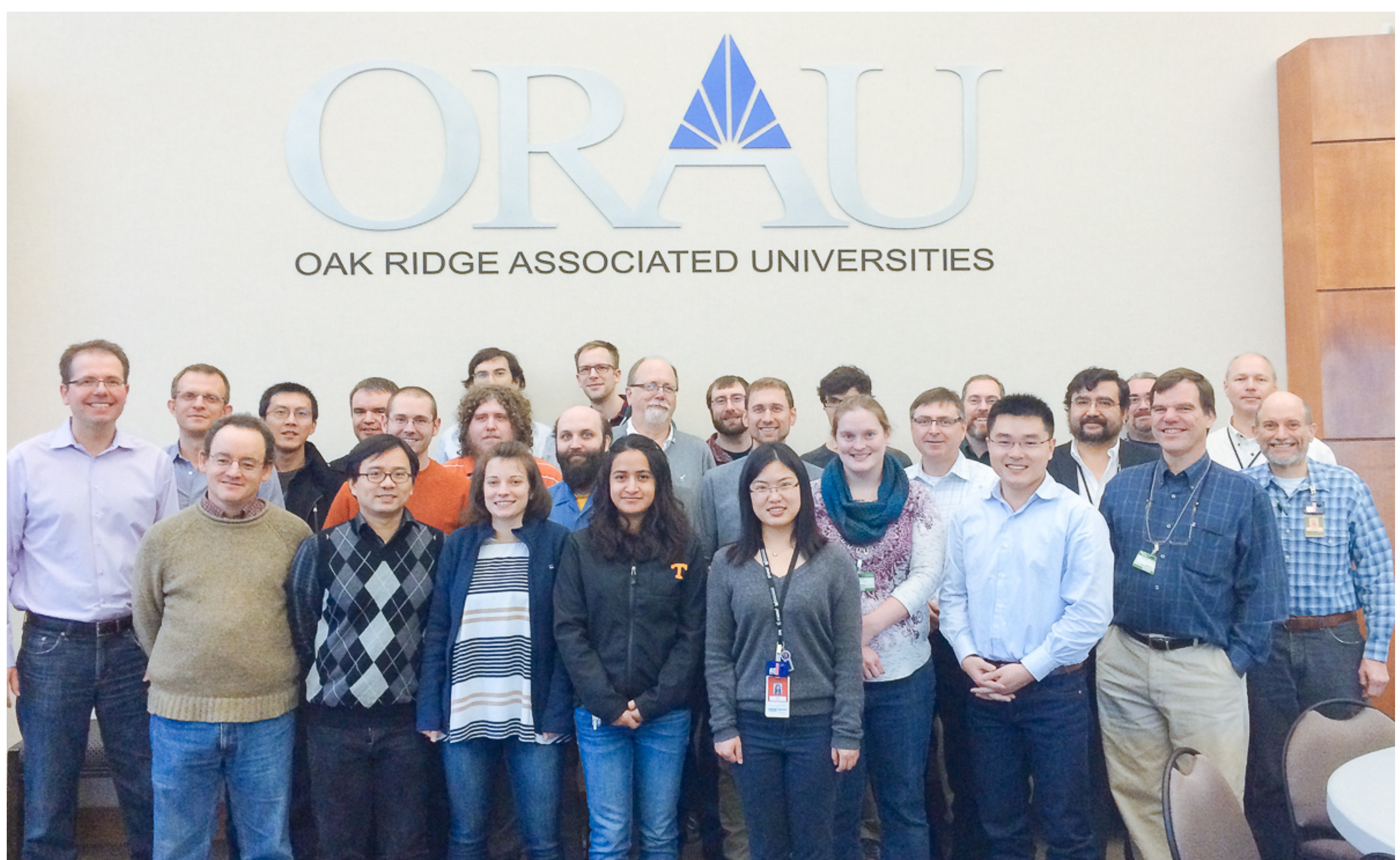
PROSPECT20 meter-long cell

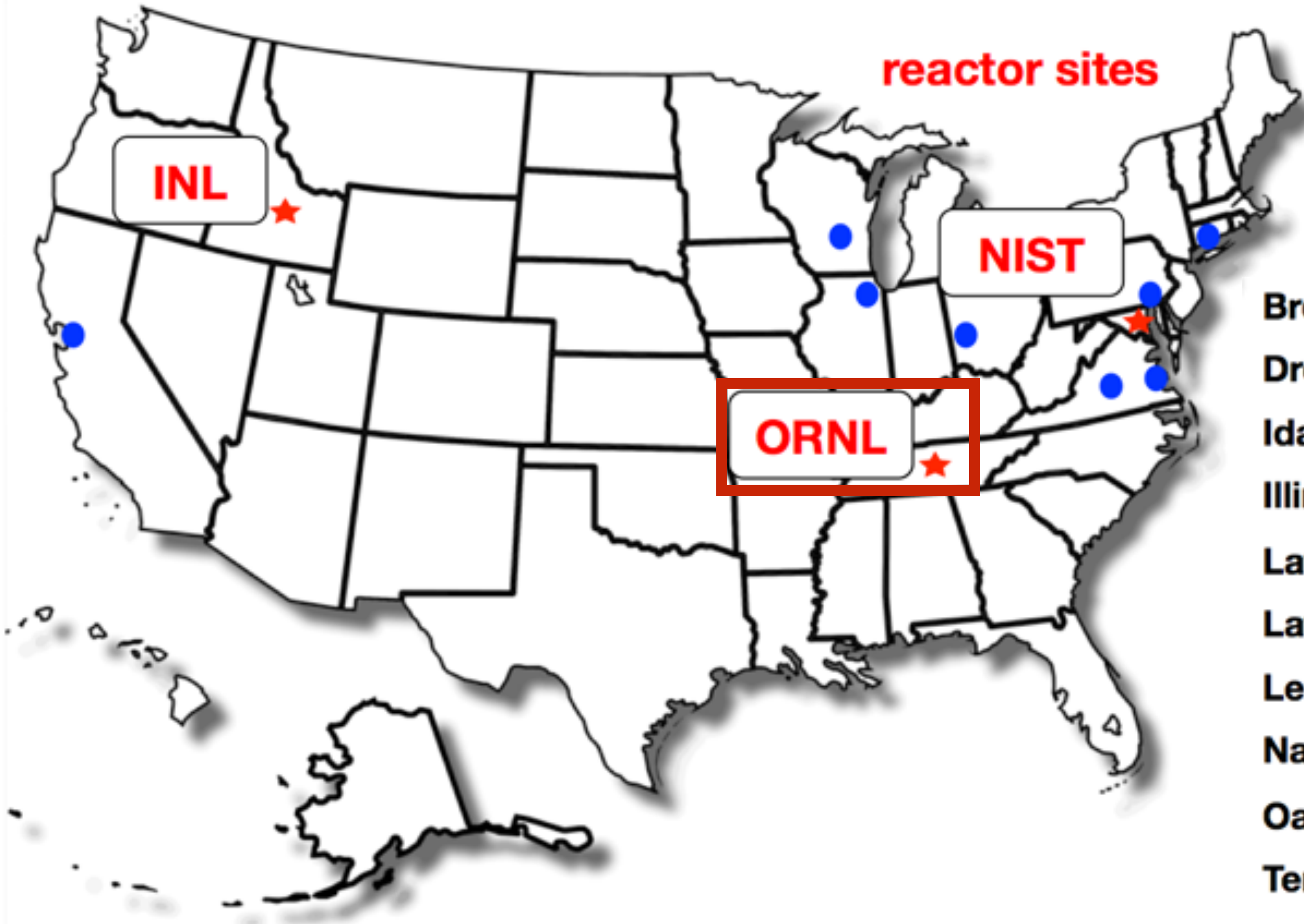
Precise Reactor Spectrum Measurements

- A lot yet to be learned from/about reactor $\bar{\nu}_e$ spectra
- In particular we could really use:
  - A high energy-resolution detector for precisely measuring absolute spectrum
  - A high position-resolution detector for comparing spectra between baselines
- Enter PROSPECT: the Precision Reactor Oscillation and SPECTrum Experiment



PROSPECT Collaboration

PROSPECT Collaboration



10 universities
6 national laboratories

Updated whitepaper
arXiv:1309.7647

Website
http://prospect.yale.edu/

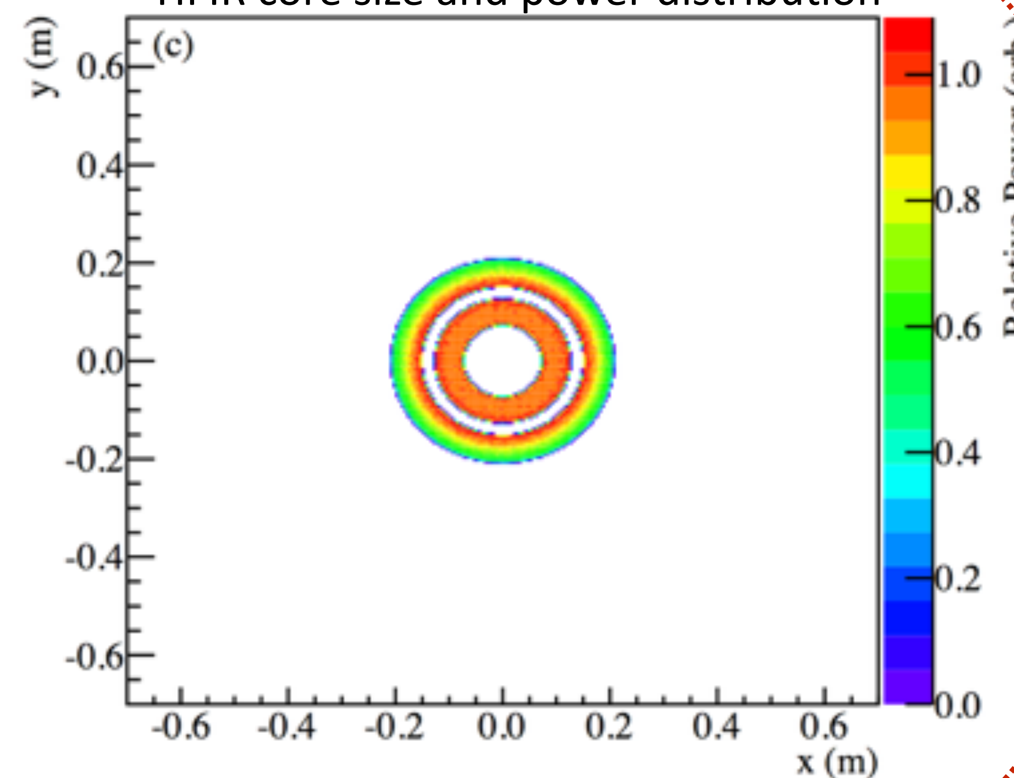
Brookhaven National Laboratory
Drexel University
Idaho National Laboratory
Illinois Institute of Technology
Lawrence Berkeley National Laboratory
Lawrence Livermore National Laboratory
Le Moyne College
National Institute of Standards and Technology
Oak Ridge National Laboratory
Temple University
University of Tennessee
Virginia Tech University
University of Waterloo
University of Wisconsin
College of William and Mary
Yale University

High-Flux Isotope Reactor at ORNL

- Compact 85MW Core
- HEU: constant U-235 $\bar{\nu}_e$ spectrum
- 42% reactor up-time (5 yearly cycles)
- Available detector location at 6+ m
- Have surveyed reactor backgrounds

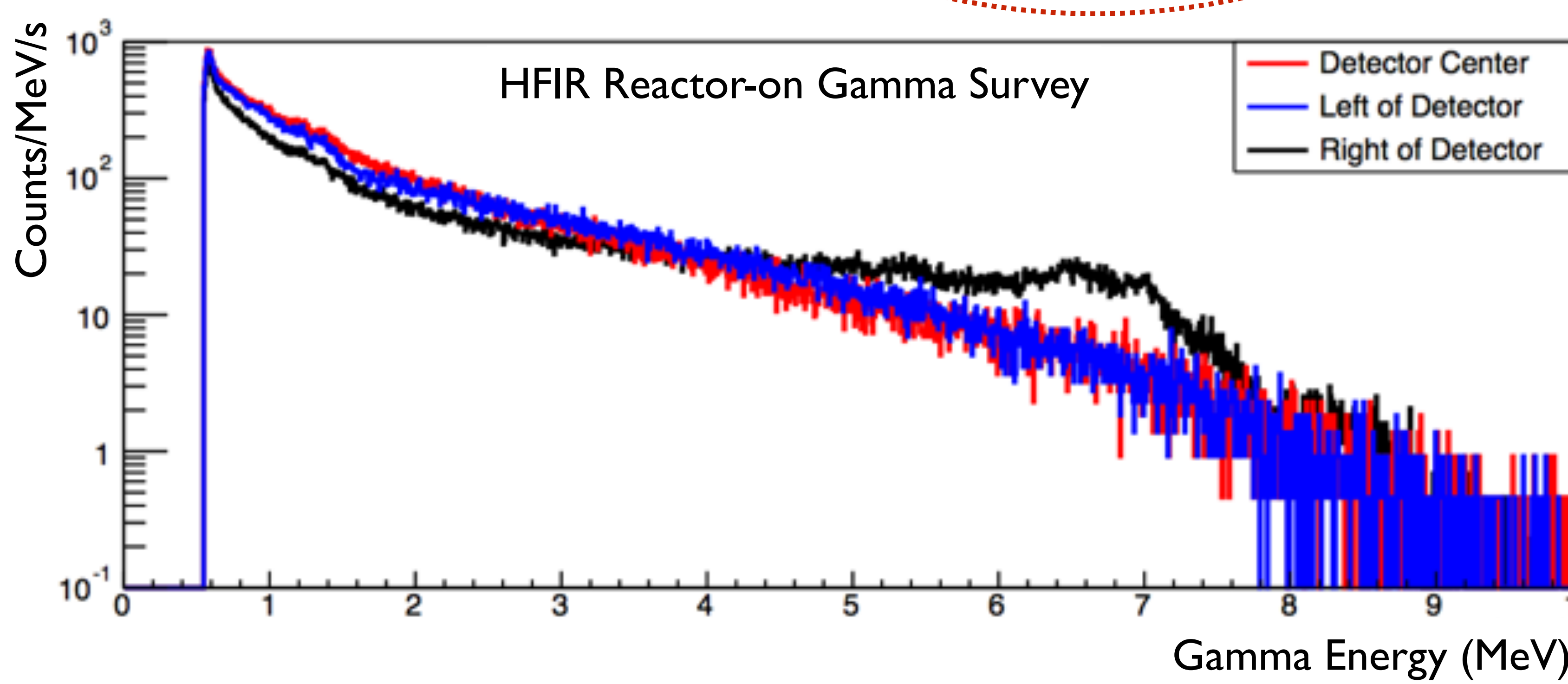
Commercial core size

HFIR core size and power distribution



HFIR gamma background survey

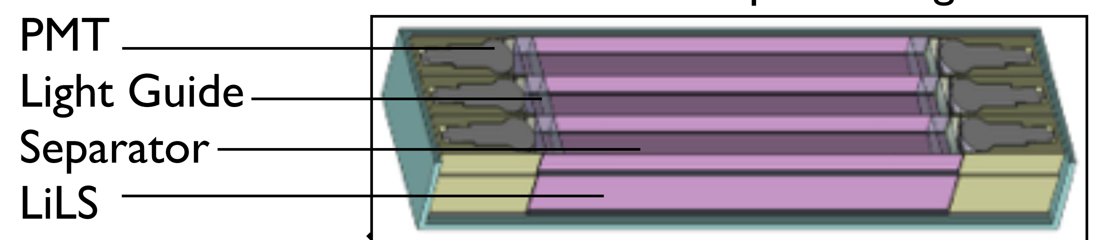
HFIR core viewed from above

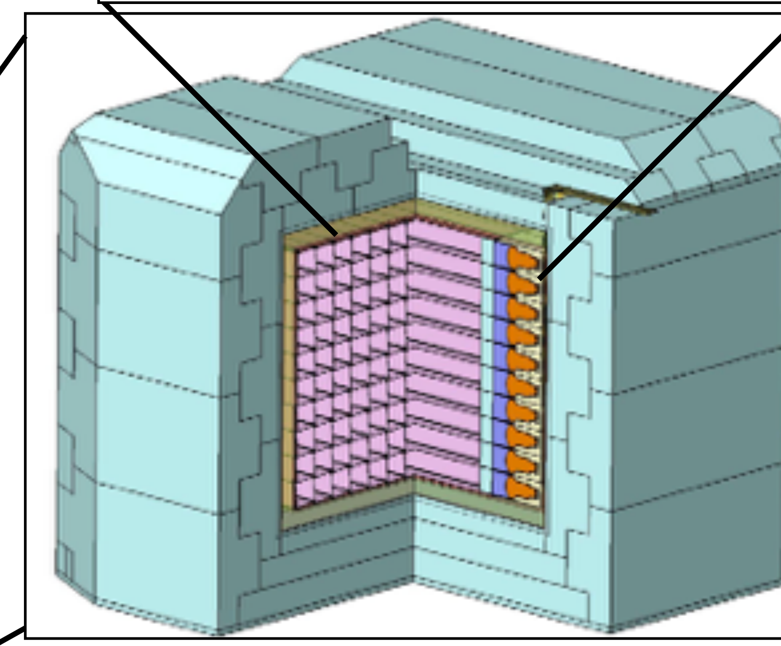


PROSPECT Experimental Layout

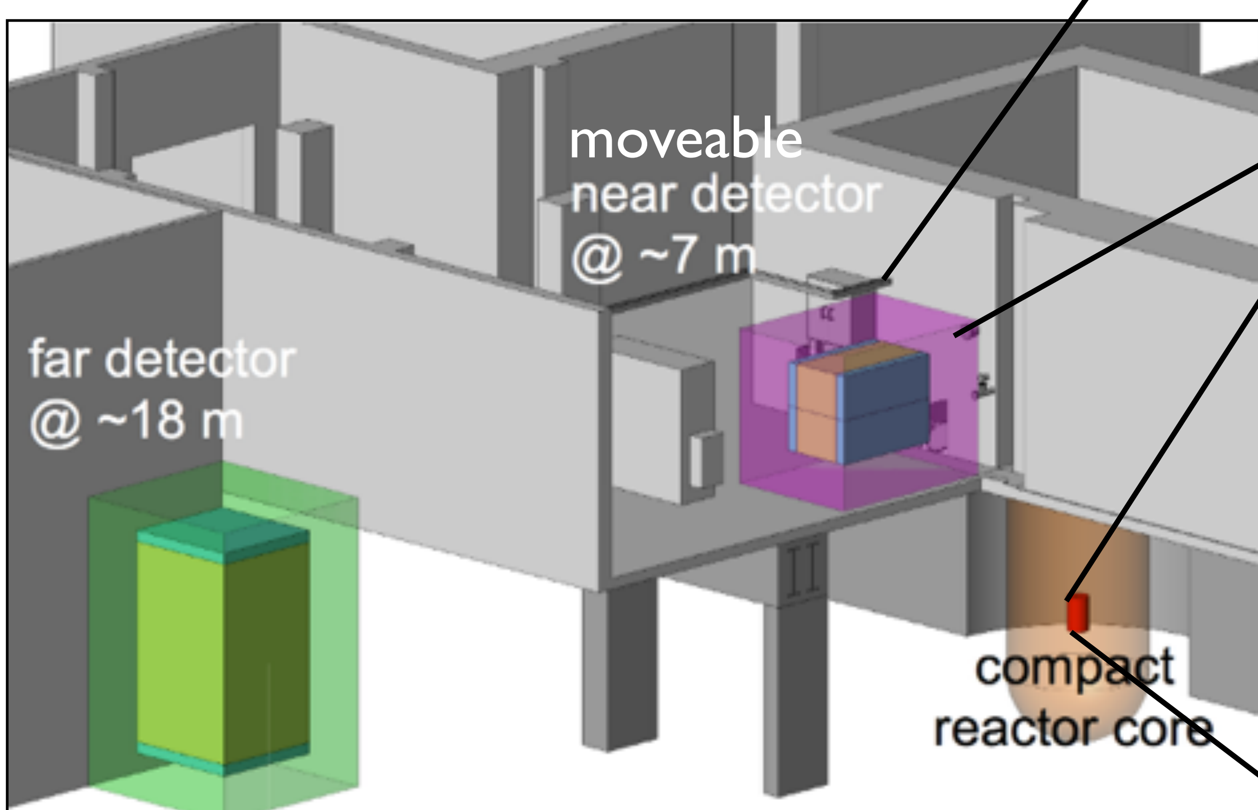
- High Flux Isotope Reactor: ORNL
- Extensive passive shielding
- Segmented liquid scintillator target region: ~3 tons for near detector (Phase I)
- Moveable: 7-11 m baselines

Sub-cell conceptual design

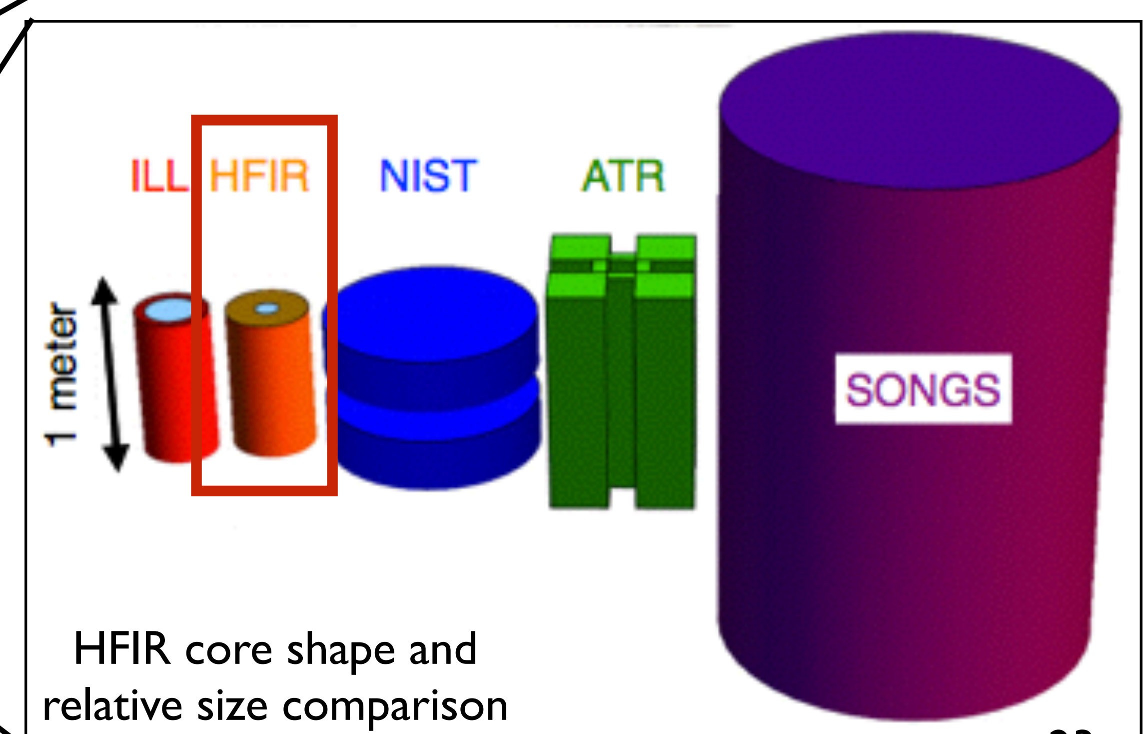




Near detector conceptual design

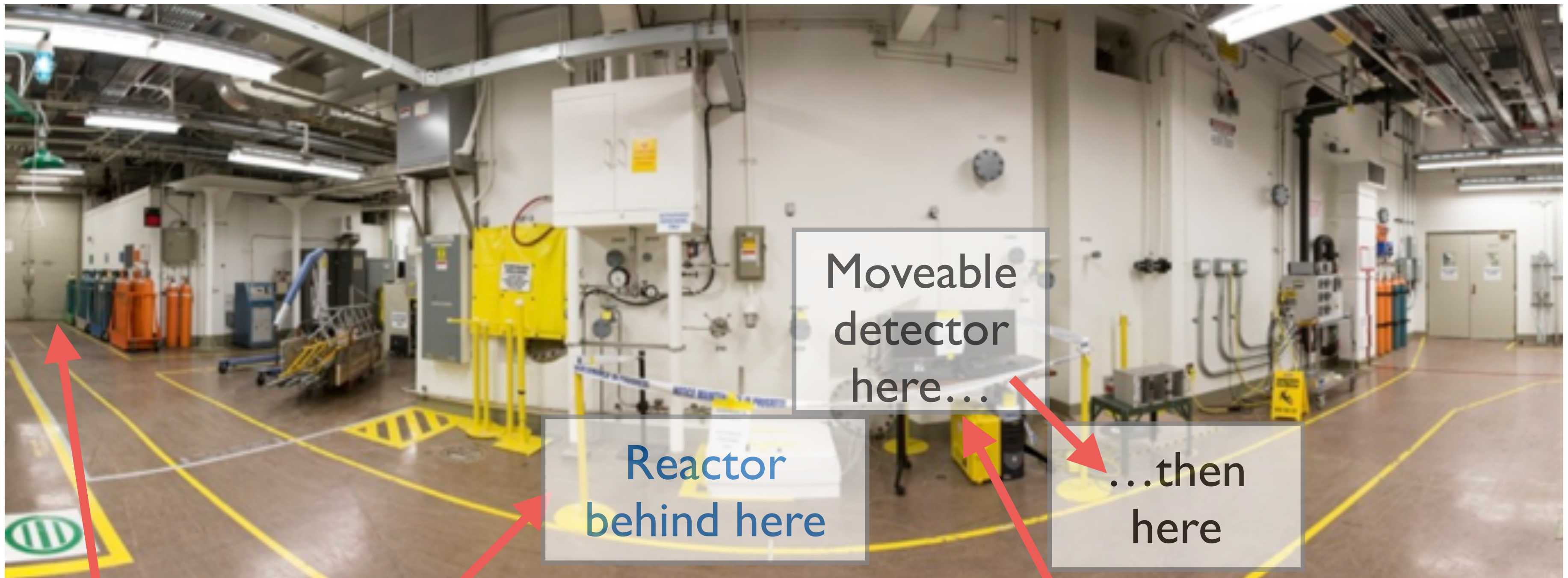


Two-detector PROSPECT deployment at HFIR



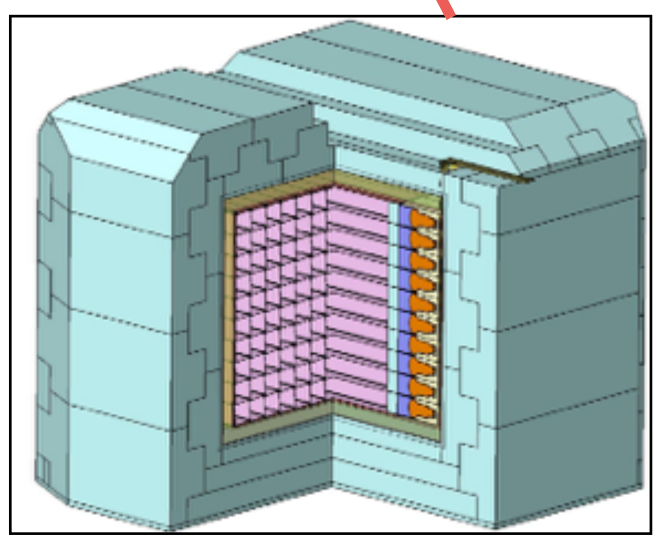
HFIR core shape and relative size comparison

PROSPECT Location at HFIR

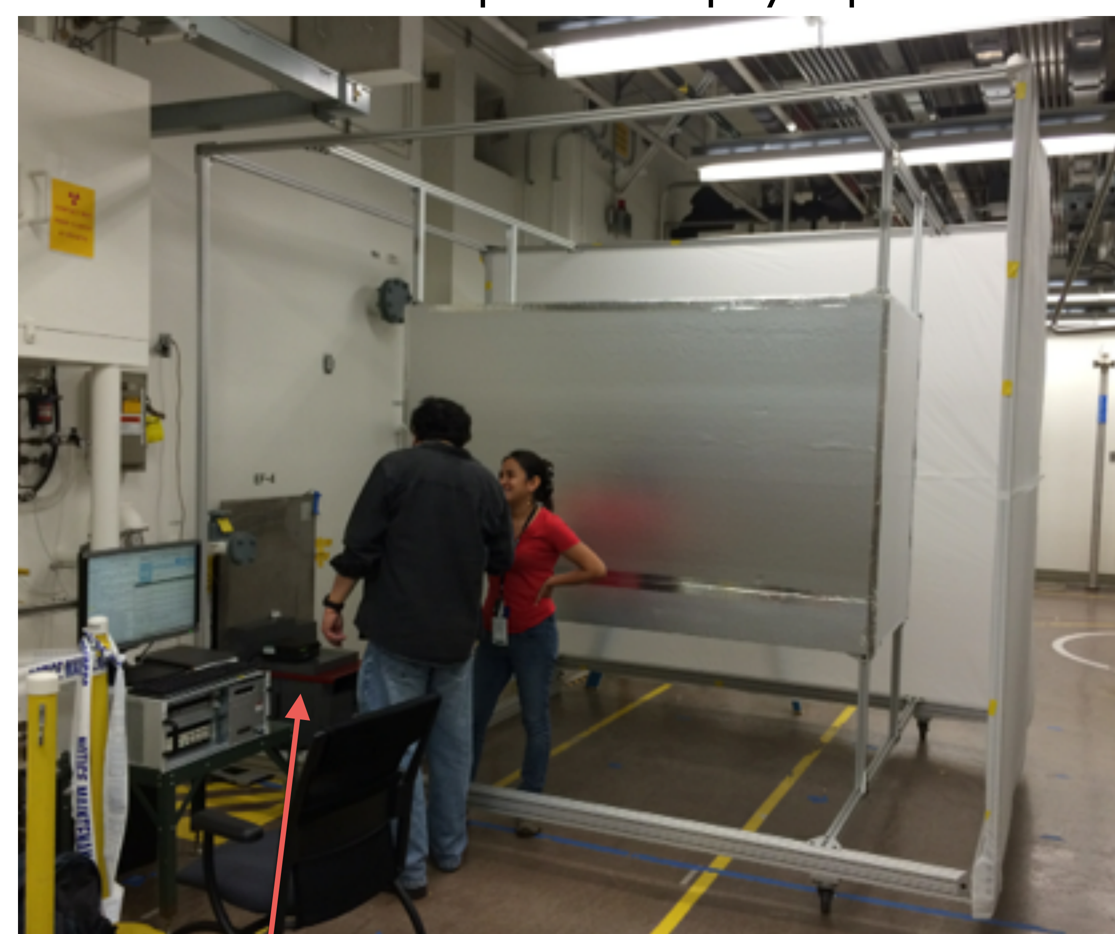


HFIR Main Level Hallway

Wide door to grade level: bring detector subsystems in here



Detector mockup in true deployed position

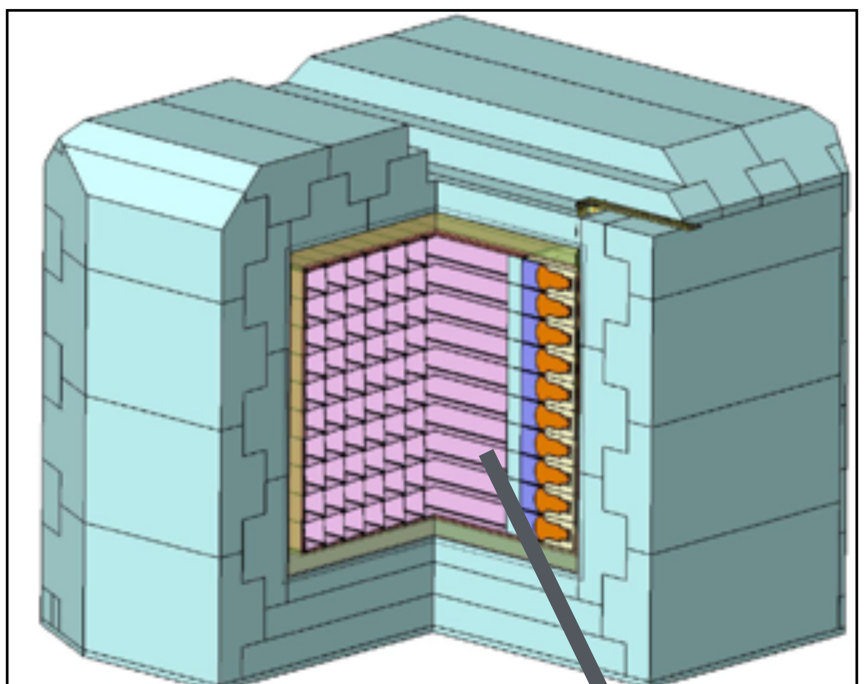


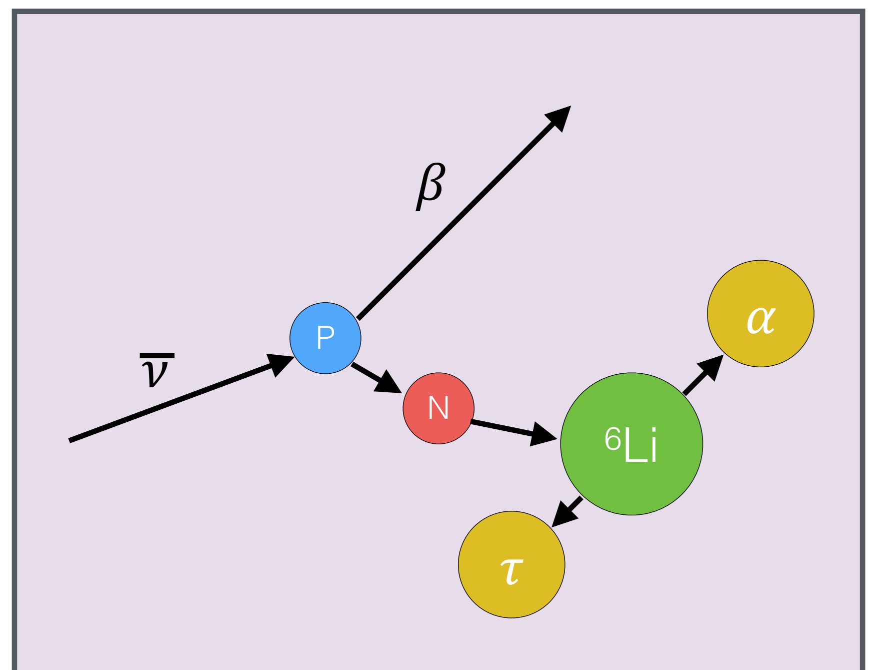
Gamma background survey detectors

Have been working in this location for > 1 year; PROSPECT prototypes operating here since August 2014!

IBD Detection in Target

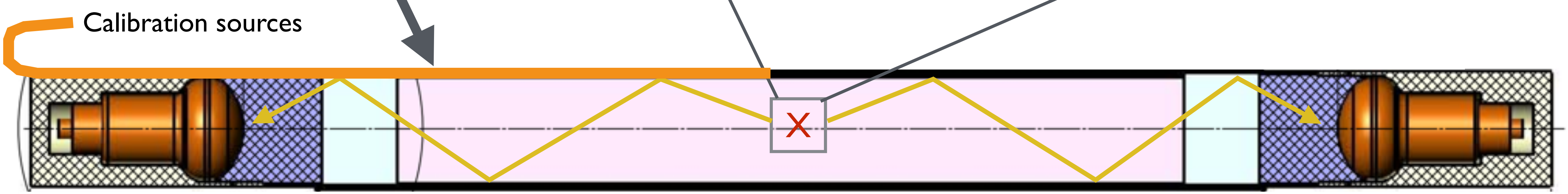
- Inverse beta interactions in Li-loaded PSD liquid scintillator
- 10 x 14 optically decoupled cells: ~15cm x 15cm x 100cm each
- Specularly reflecting cell walls quickly guide light to PMTs
- System can meet position/energy resolution requirements





Prompt signal: 1-10 MeV positron from inverse beta decay (IBD)

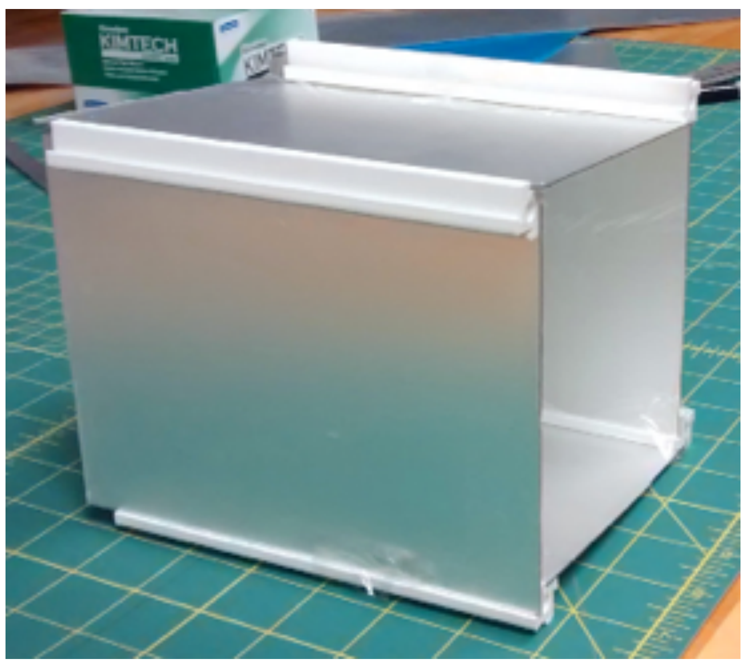
Delay signal: ~0.5 MeV signal from neutron capture on ^{6}Li



Key Components For R&D

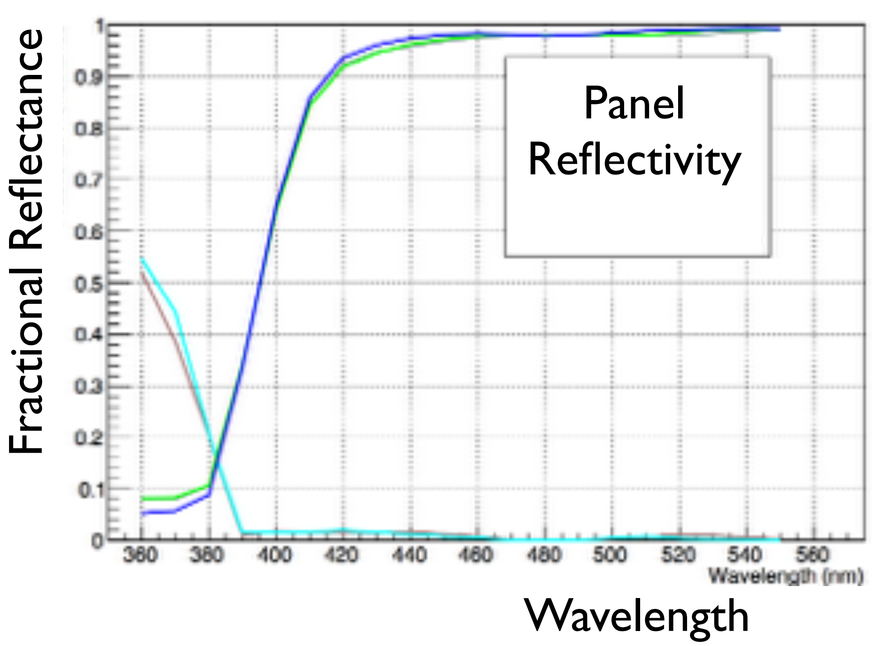
• Reflecting segment system

- Fabrication methods identified
- Testing differing materials



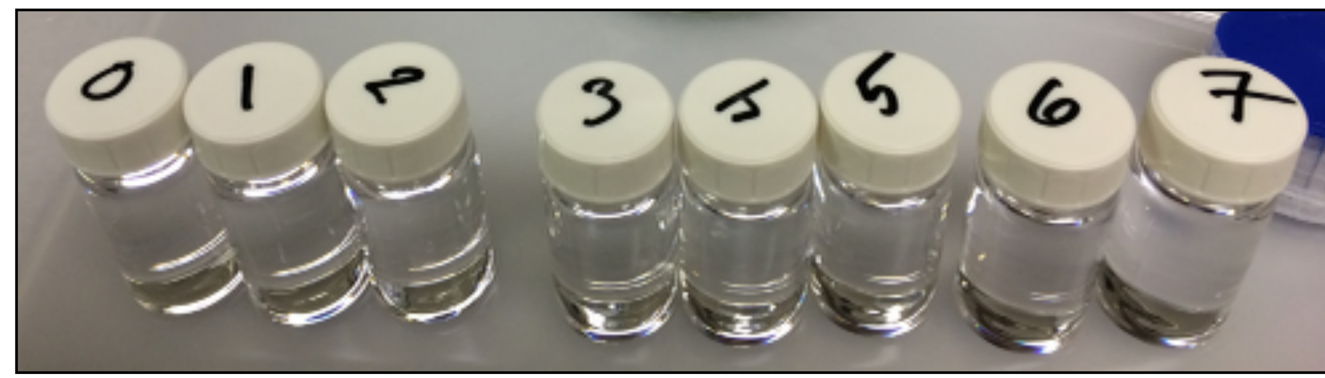
Short Mockup Segment

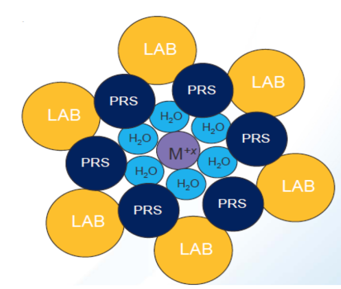
Specular Panel



• Li-loaded Scintillator

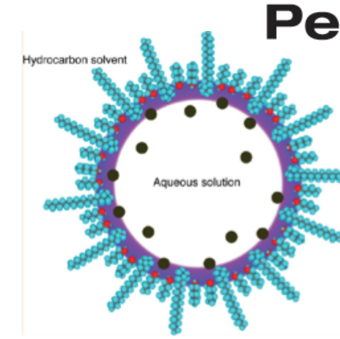
- Many methods identified
- Final choice: Eljen EJ-309 scintillator with ^{6}Li doping (BNL)





PSD enhanced LAB-LS doped with BNL ^{6}Li chemistry

PerkinElmer®



Ultima-Gold doped with NIST ^{6}Li micro-emulsion

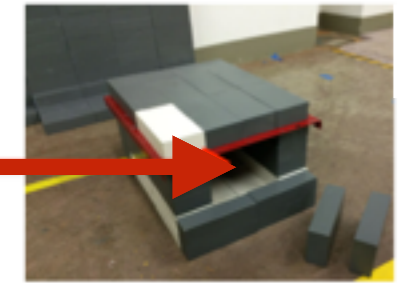
PROSPECT Prototype Demonstrations

Run DAQ, Remote data-taking

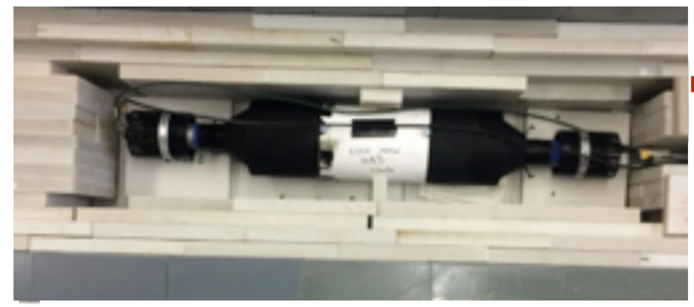
See n-Li + PSD

PROSPECT 0.1*
Aug 2014

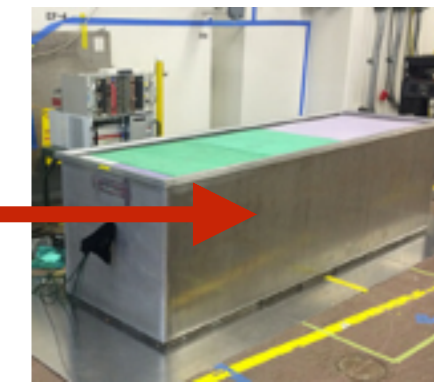
2 inches



PROSPECT 2*
Dec 2014 - Mar 2015



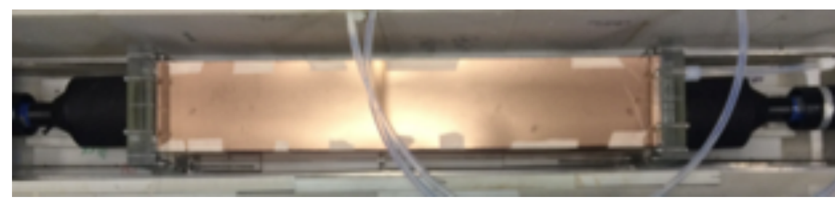
5 inches



Demonstrate shielded background rates

Demonstrate full timing and PE response

PROSPECT 20*
Mar 2015



1 meter

PROSPECT 200

3x3x1meter mockup at IIT

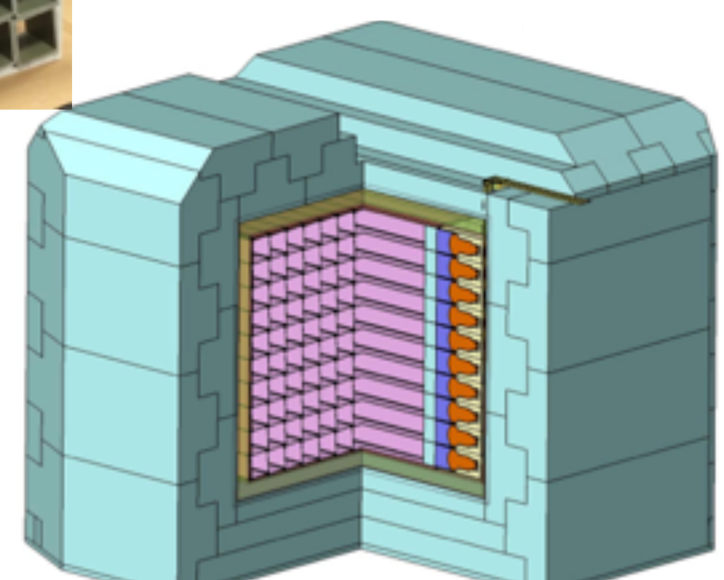
Deploy final design concepts

Observe relative segment responses

See antineutrinos

Meet physics goals

PROSPECT 2ton



* Deployment complete!!!!

Approximate mass kg

PROSPECT Prototype Demonstrations

✓ Run DAQ, Remote data-taking

✓ See n-Li + PSD

✓ Demonstrate shielded background rates

✓ Demonstrate full timing and PE response

Deploy final design concepts

Observe relative segment responses

See antineutrinos

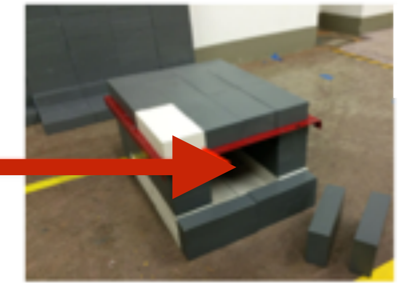
Meet physics goals

* Deployment complete!!!!

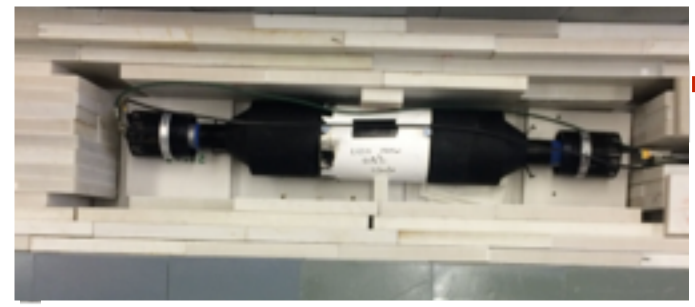
Approximate mass kg

PROSPECT 0.1 *
Aug 2014

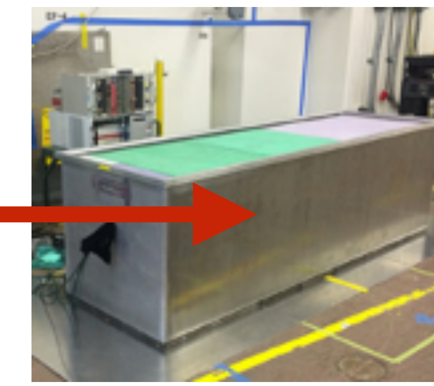
2 inches



PROSPECT 2 *
Dec 2014 - Mar 2015



5 inches



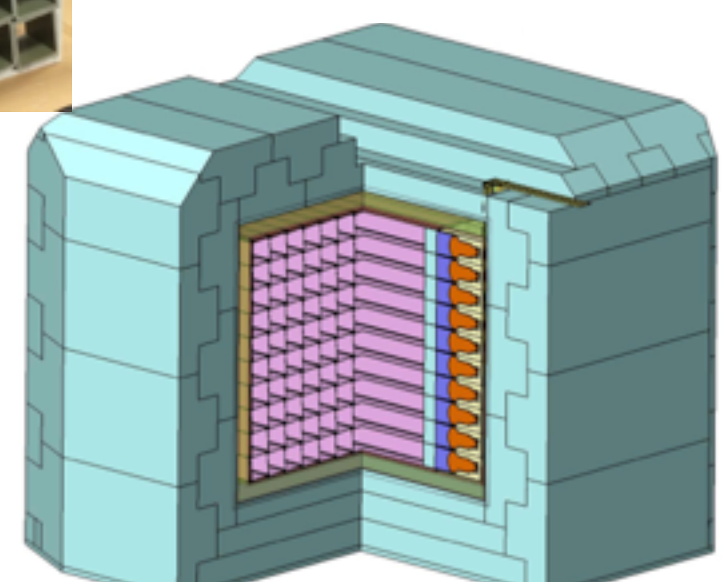
PROSPECT 20 *
Mar 2015

1 meter

PROSPECT 200

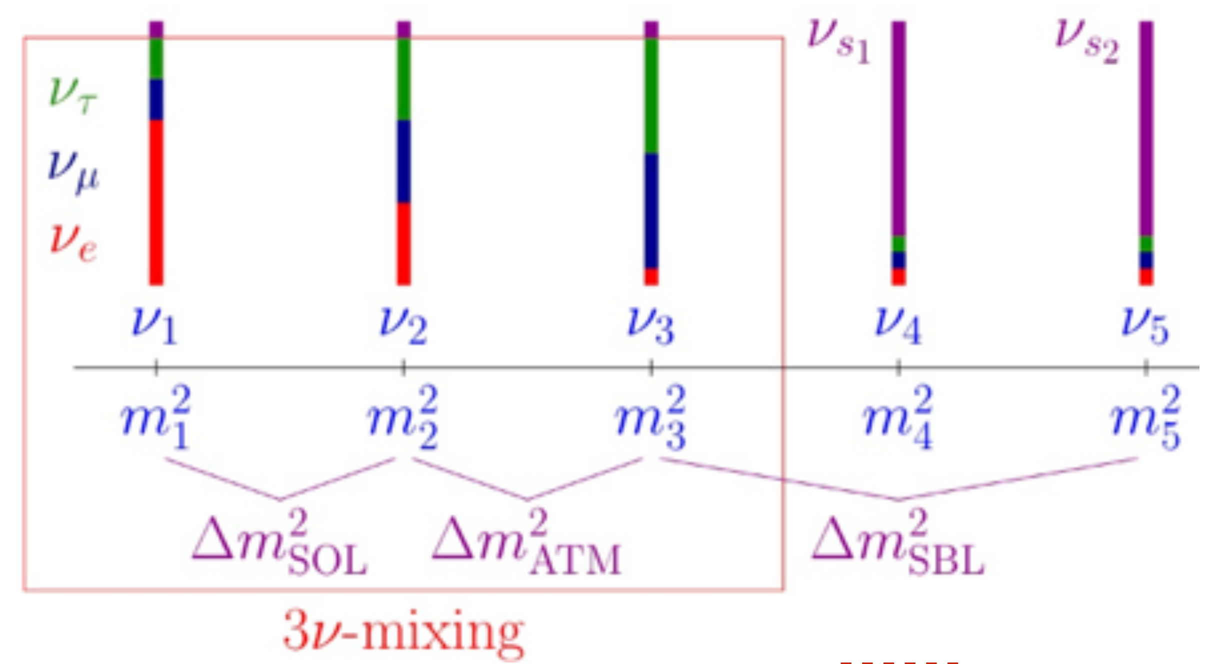
3x3x1meter mockup at IIT

PROSPECT 2ton



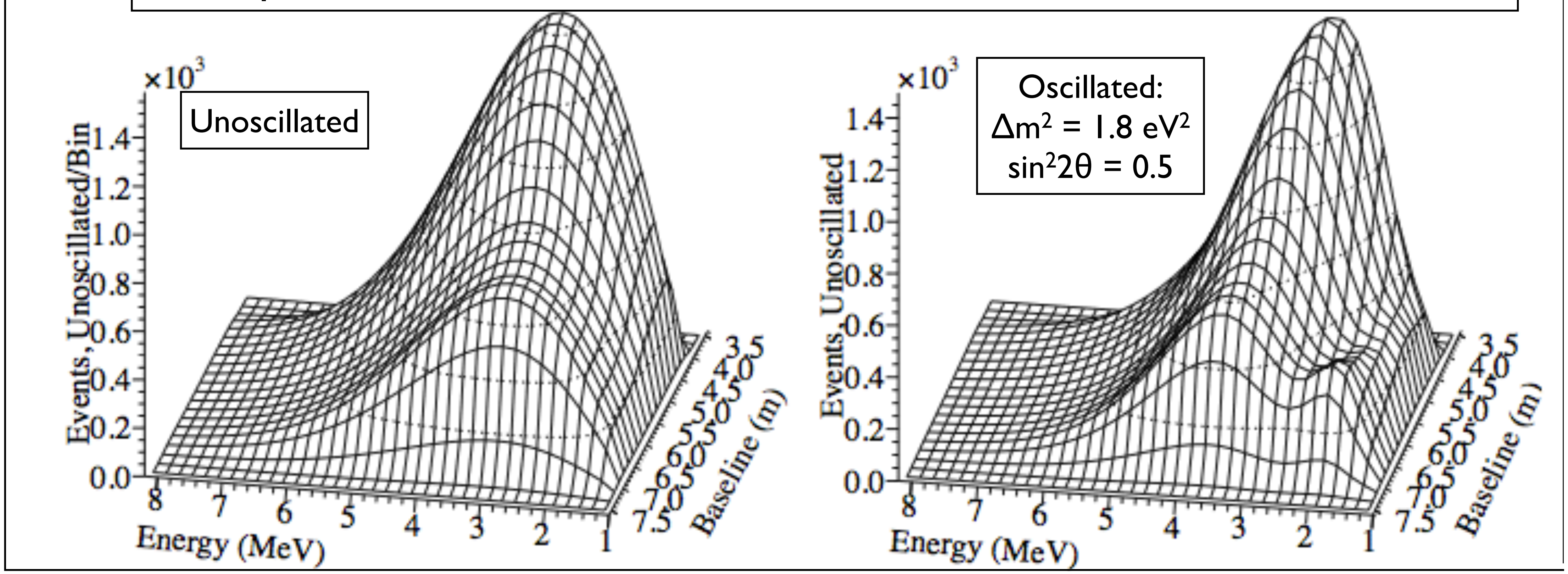
PROSPECT Physics: Oscillations

- Measure energy spectrum separately in each segment
- Look for unexpected L/E distortion: oscillations
  - Mass splitting wouldn't match observed three-neutrino splittings: fourth (sterile) neutrino



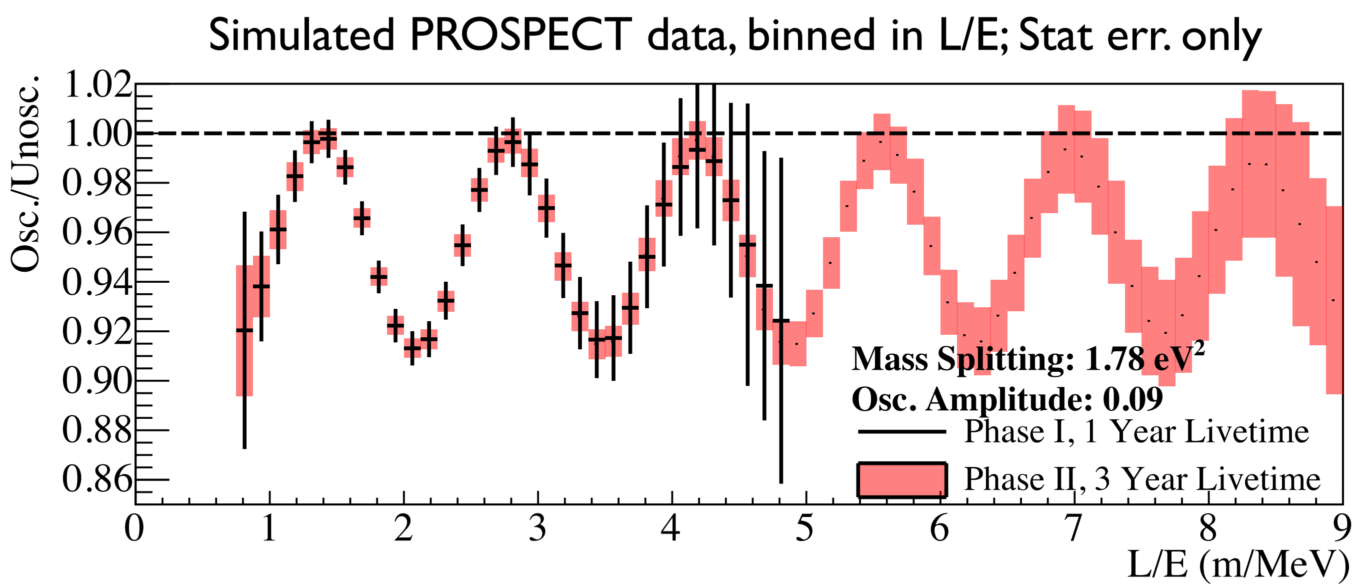
$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\boxed{\theta} \sin^2 \left[1.27 \boxed{\Delta m^2} (eV^2) \frac{\boxed{L}(km)}{\boxed{E_\nu}(GeV)} \right]$$

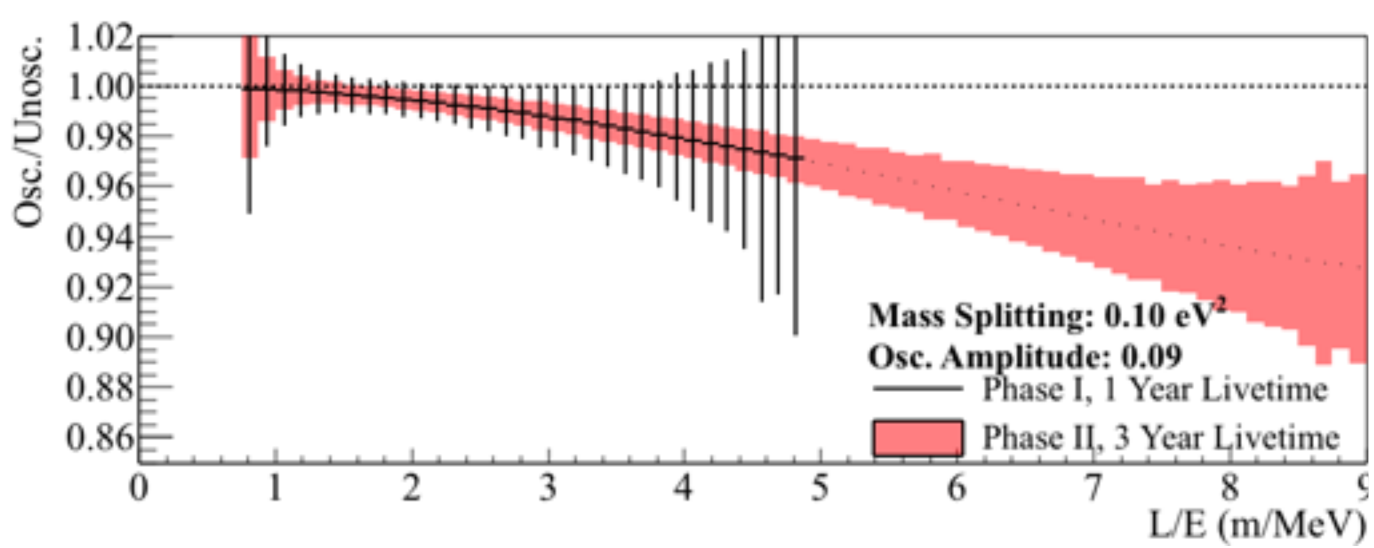
Example: 3x1x1 m^3 detector, 1m^3 20 MW HEU core, 4m closest distance

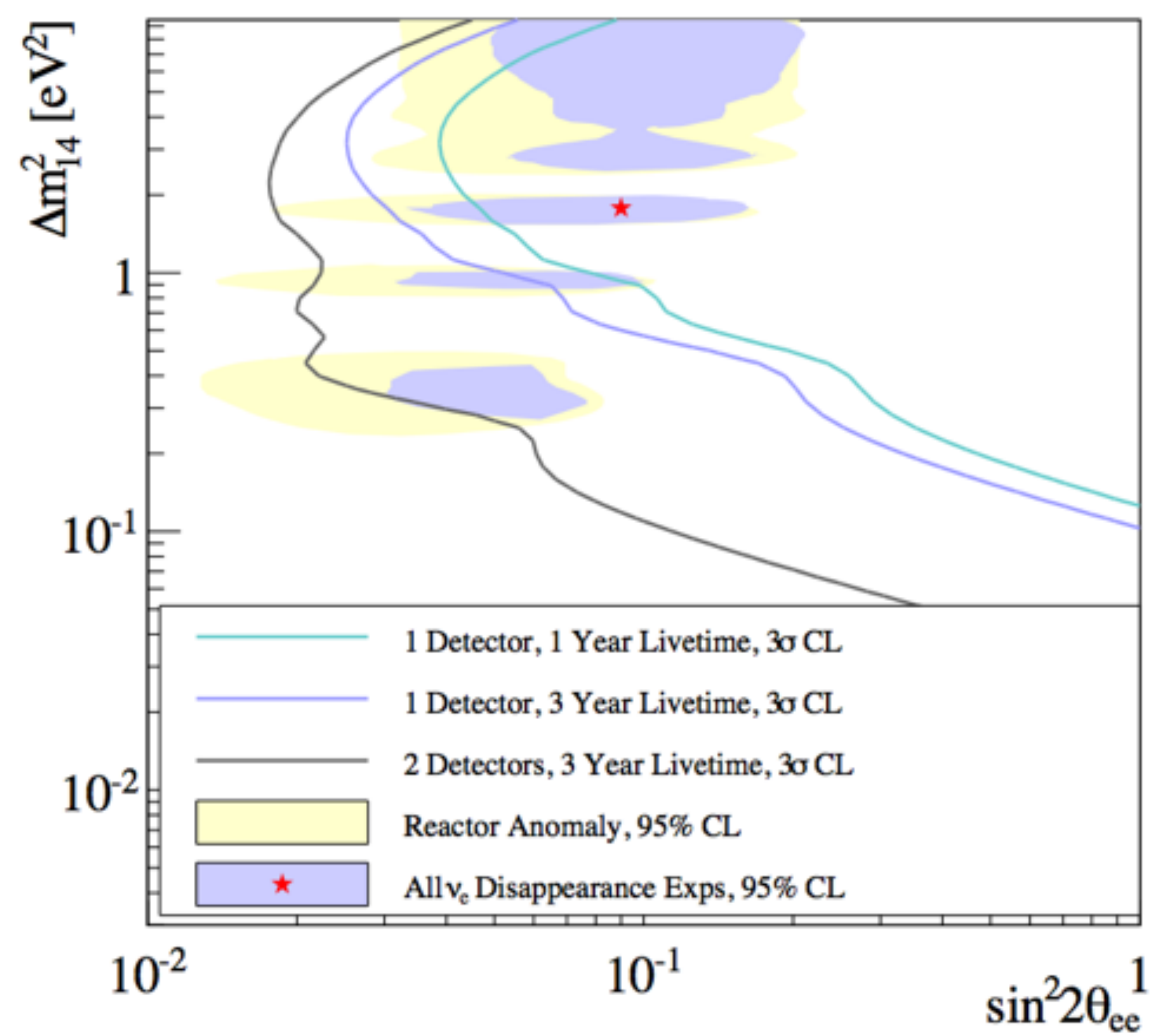


PROSPECT Physics: Oscillations

- **Excellent oscillation discovery potential at PROSPECT**
  - If new sterile neutrino is where global fits suggest, it's very likely we'll see it!
  - No reliance on absolute spectral shape or normalization: pure relative measurement
  - Good coverage with a single detector and one/three calendar years of data-taking



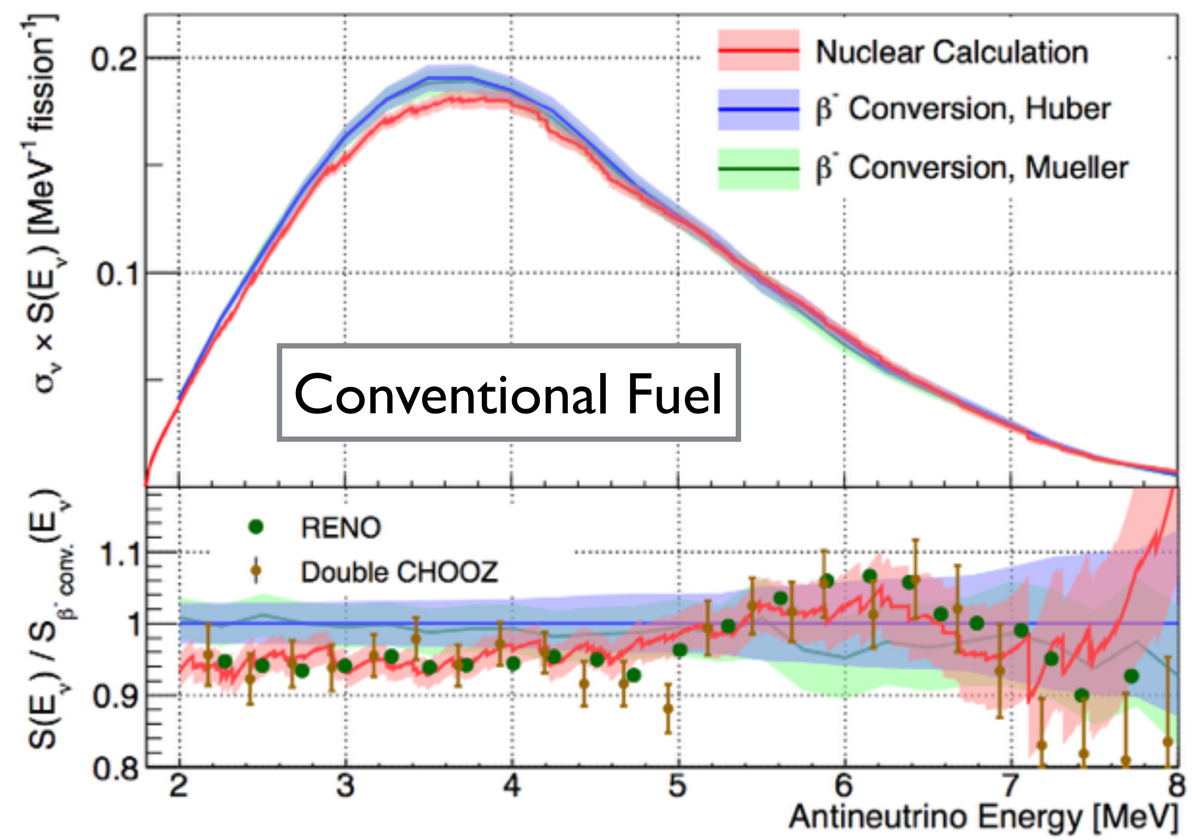


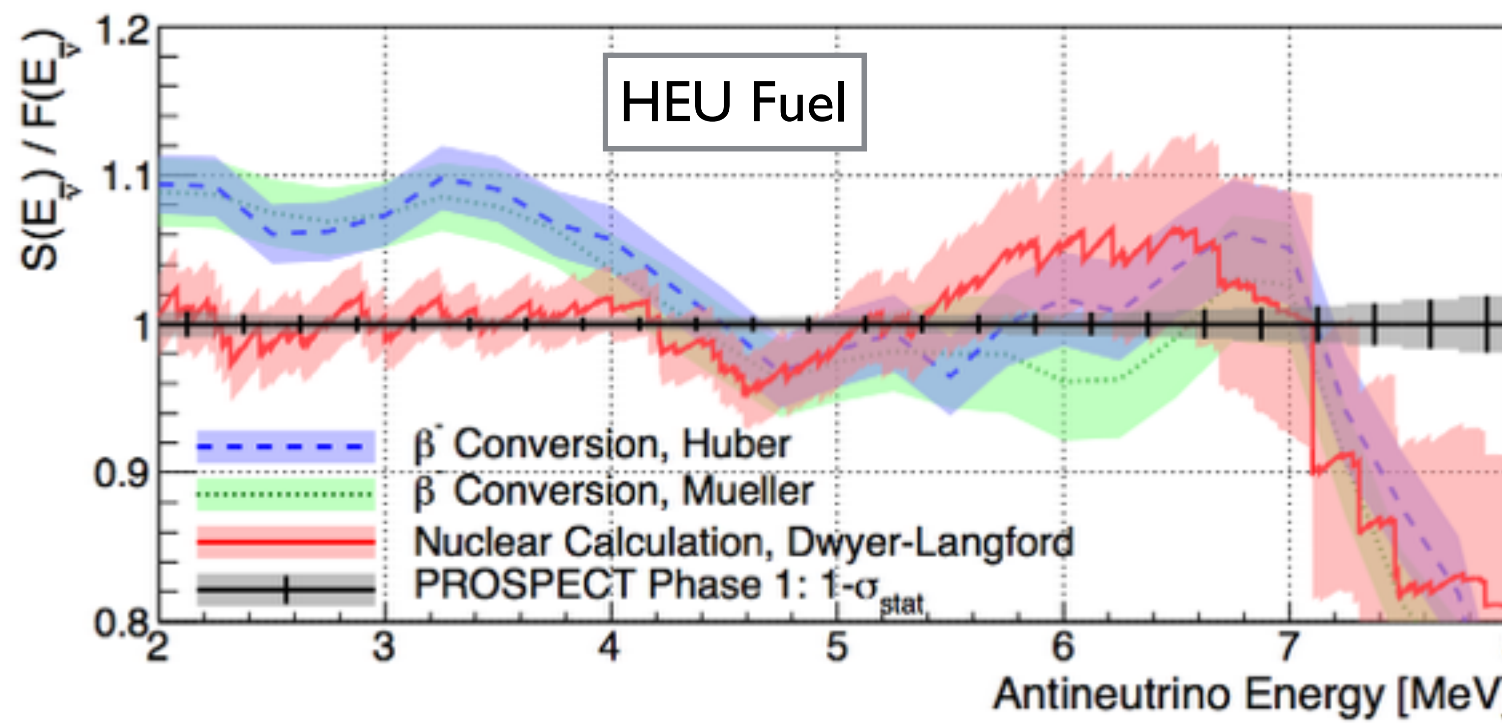


PROSPECT Physics: Absolute Spectrum

- **What is the correct model?**
  - Have data points for conventional fuel (^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu)
  - HEU (^{235}U): independent constraint
- Benefits of HFIR:
  - 1 core versus many cores (Daya Bay, RENO)
  - Easier model: only 1 isotope, no time-dependence
- Implications for reactor monitoring:
  - Example: what if 5MeV bump isn't present for HEU fuel?
  - In that case 'bump' size would be a proxy for ^{239}Pu concentration in core

Dwyer and Langford, arxiv:[nucl-ex]1407.1281 (2014)

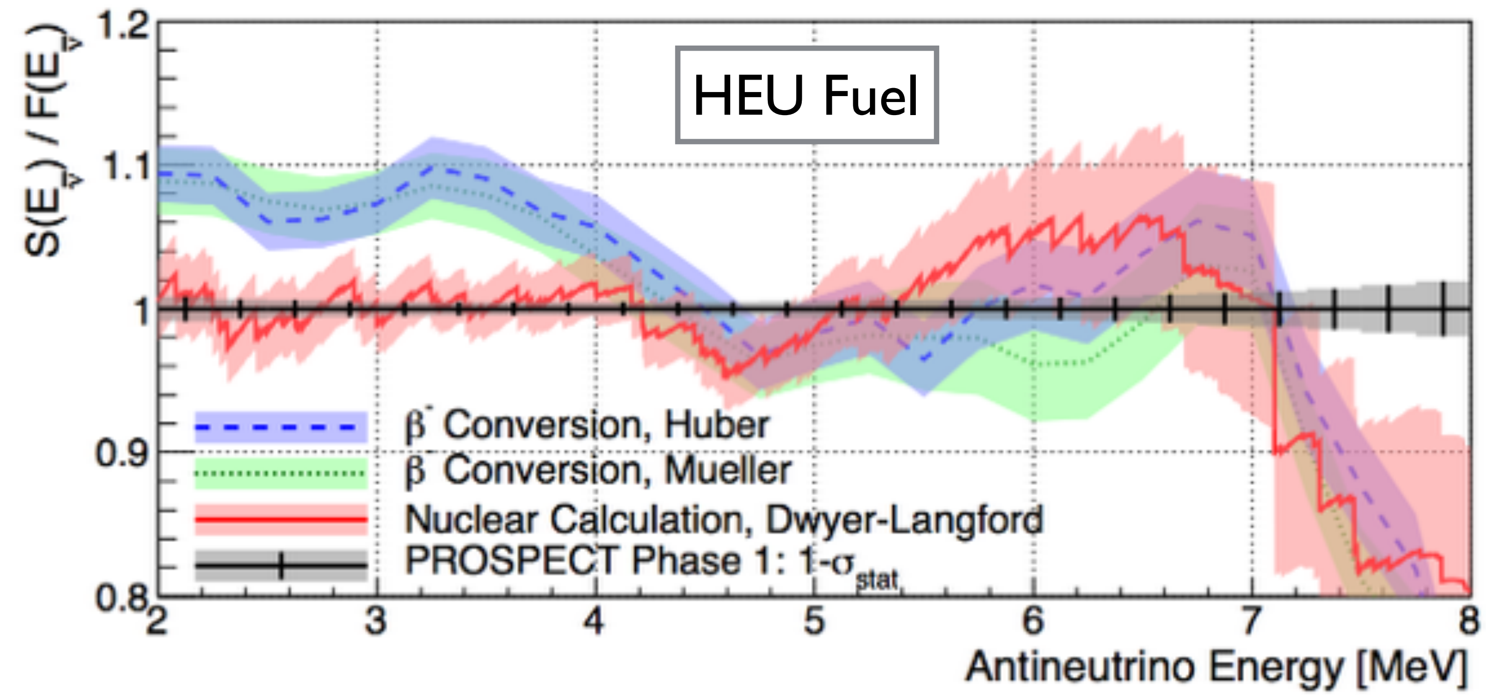


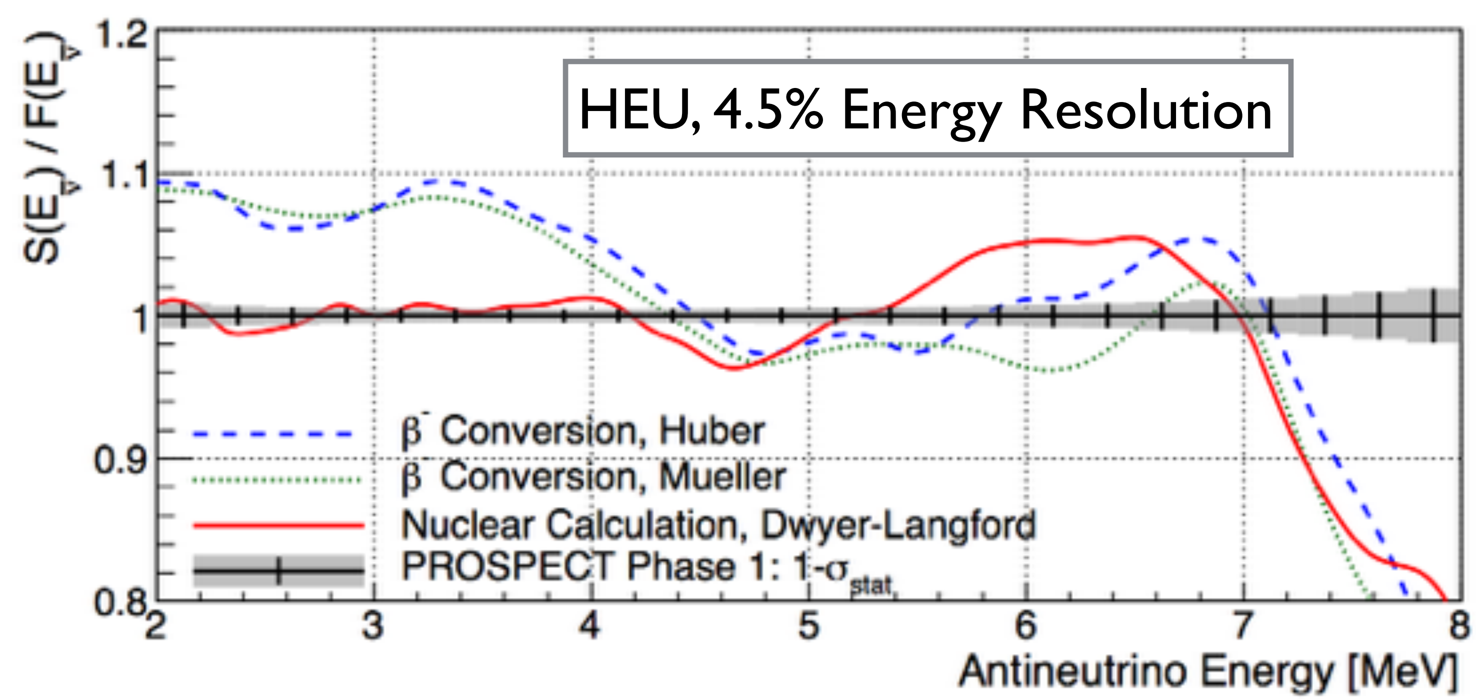


PROSPECT Physics: Absolute Spectrum

- How much fine structure exists in reactor spectrum?
  - Ab initio calculations suggest significant fine structure from endpoints of prominent beta branches

- PROSPECT can provide highest-ever energy resolution on the spectrum
  - Thus, will give best fine structure measurement
  - Goal resolution: 4-5%
  - Provide constraints on individual beta branches (reactor spectroscopy)?
  - Input for next reactor experiments (JUNO)?





Demonstrating Key Requirements

- To accomplish these physics goals, PROSPECT needs:
  - Control of backgrounds at on-surface near-reactor location
  - Understanding of energy scale and energy resolution
  - Understanding of position reconstruction ability
- Pre-PROSPECT program should demonstrate PROSPECT's abilities in all three of these areas.

IBD Detection and Backgrounds

- Have a highly sensitive detector operating at the surface in the direct vicinity of an operating nuclear reactor
- Major design challenge: background reduction
- Aiming for S:B ratio of 1:1

Signal, Main Backgrounds

Inverse Beta Decay

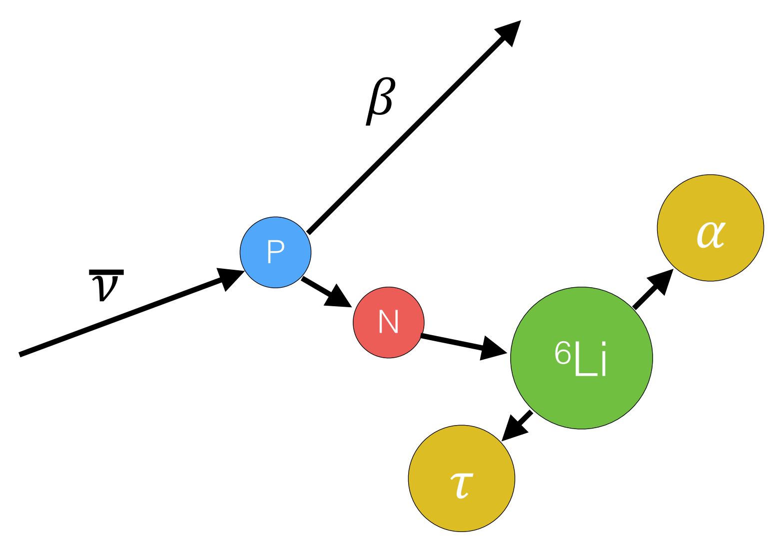
γ-like prompt, n-like delay

Fast Neutron

n-like prompt, n-like delay

Accidentals

γ-like prompt, γ-like delay

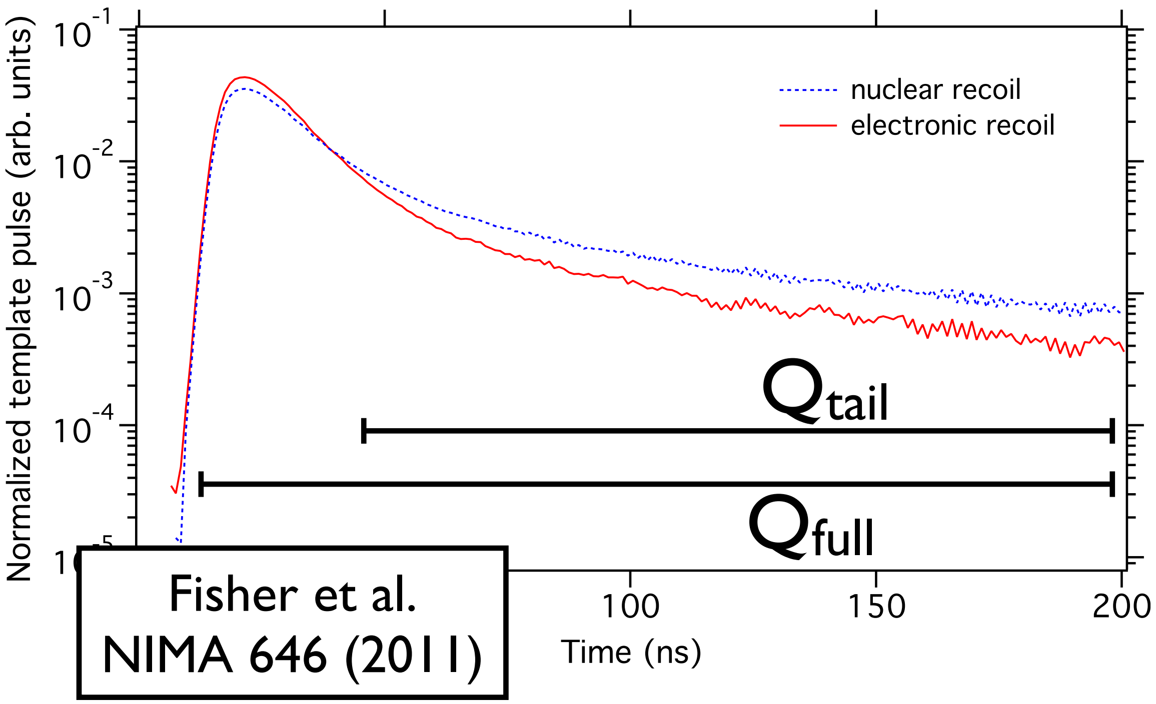


Prompt signal: 1-10 MeV positron from inverse beta decay (IBD)

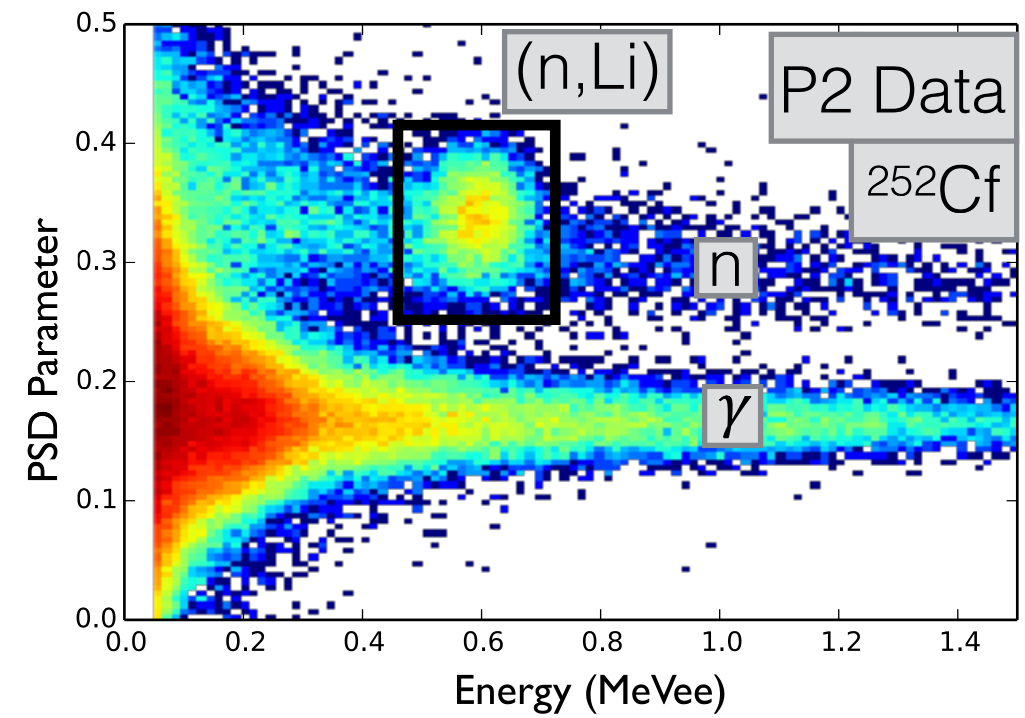
Delay signal: ~0.5 MeV signal from neutron capture on ^{6}Li

Background Rejection, Signal Selection

- Reduce backgrounds: Li-capture and pulse-shape discrimination



$$PSD = \frac{Q_{tail}}{Q_{full}}$$



Signal, Main Backgrounds

Inverse Beta Decay

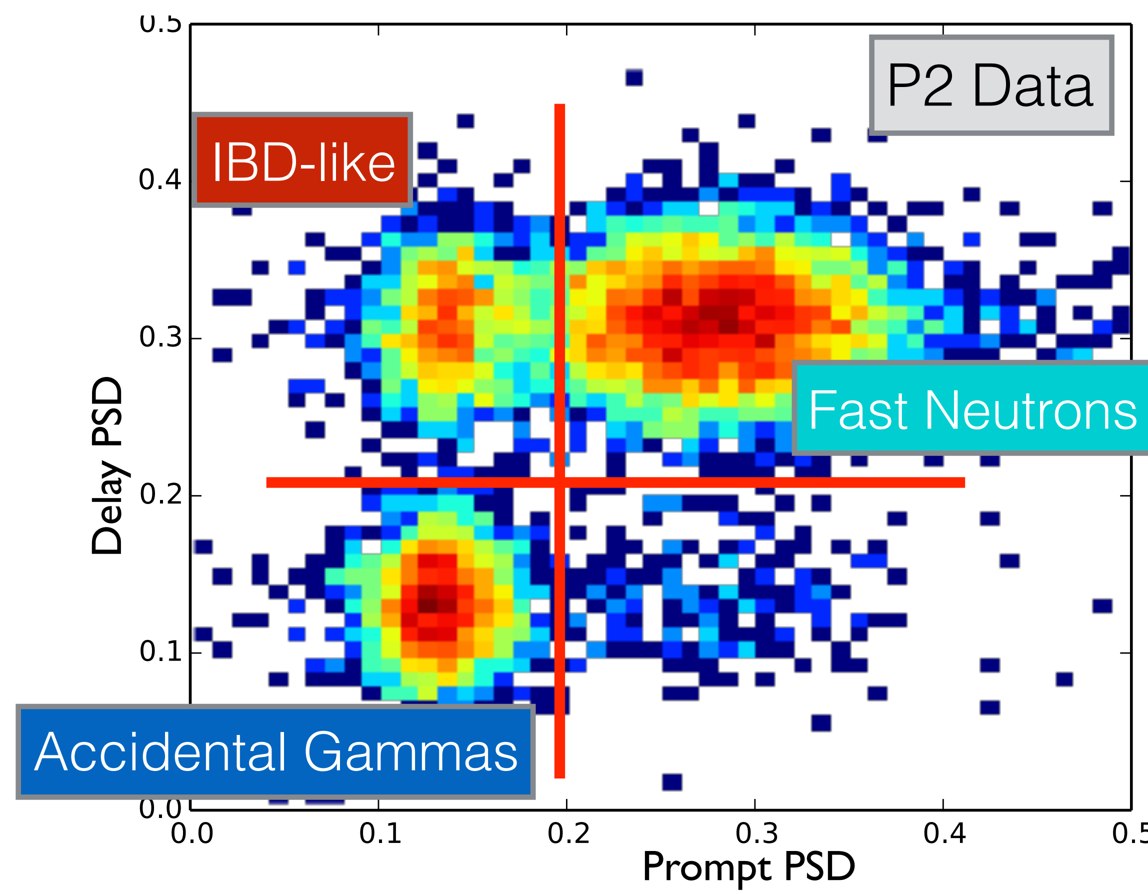
γ-like prompt, n-like delay

Fast Neutron

n-like ~~prompt, n-like~~ delay

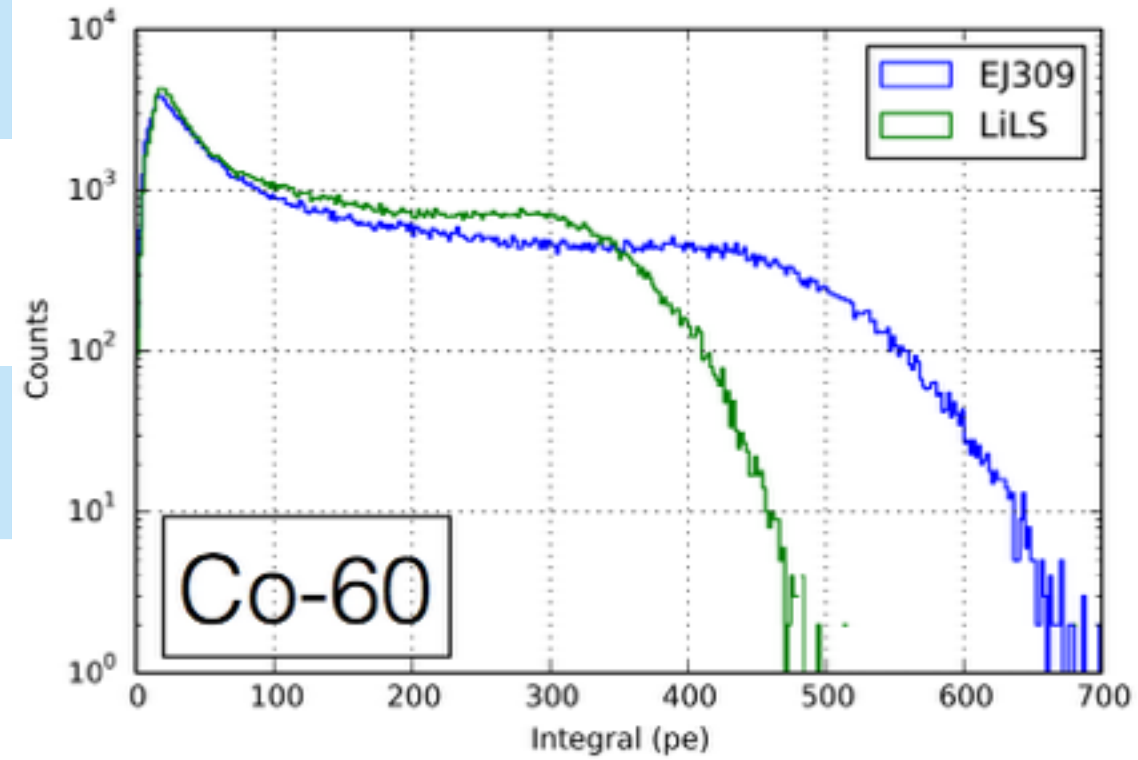
Accidentals

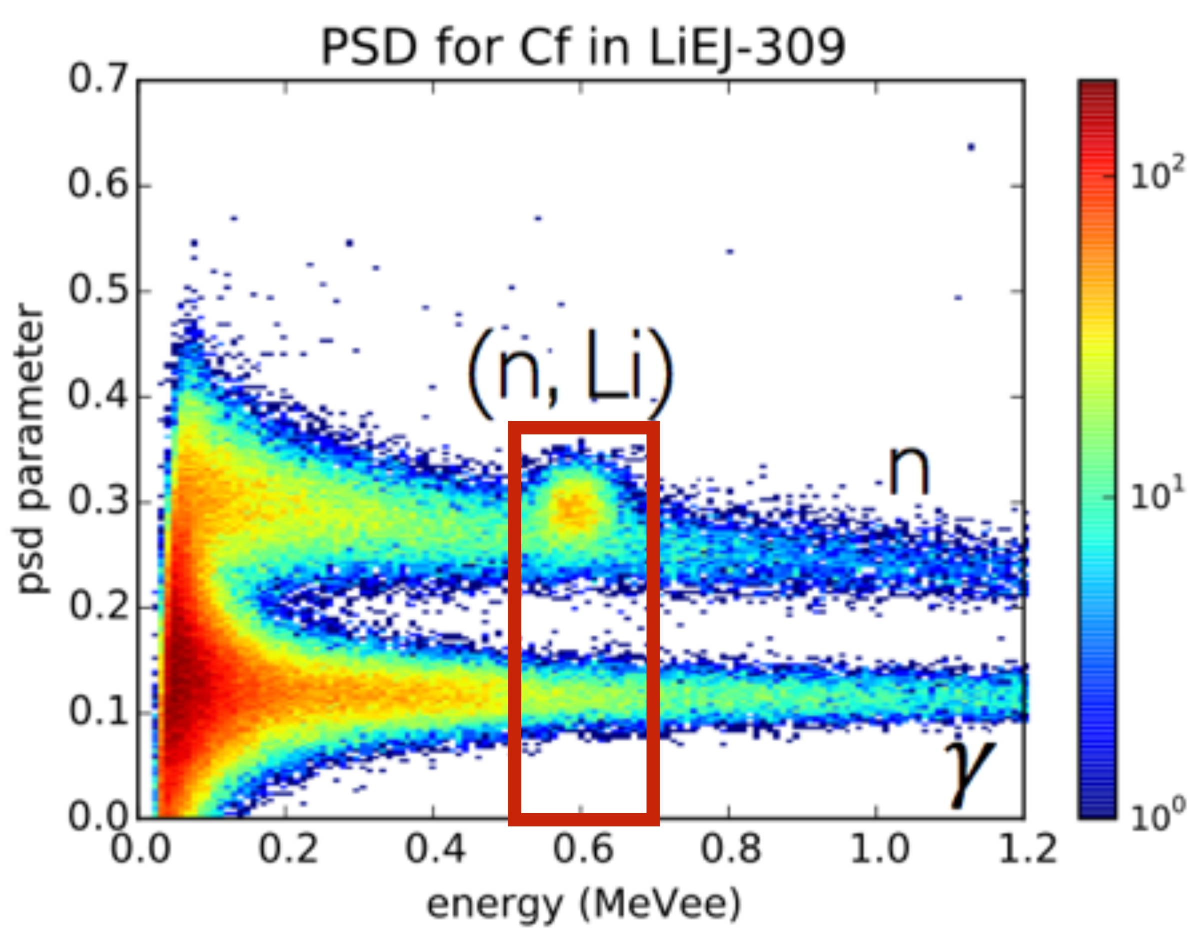
γ-like ~~prompt, γ-like~~ delay

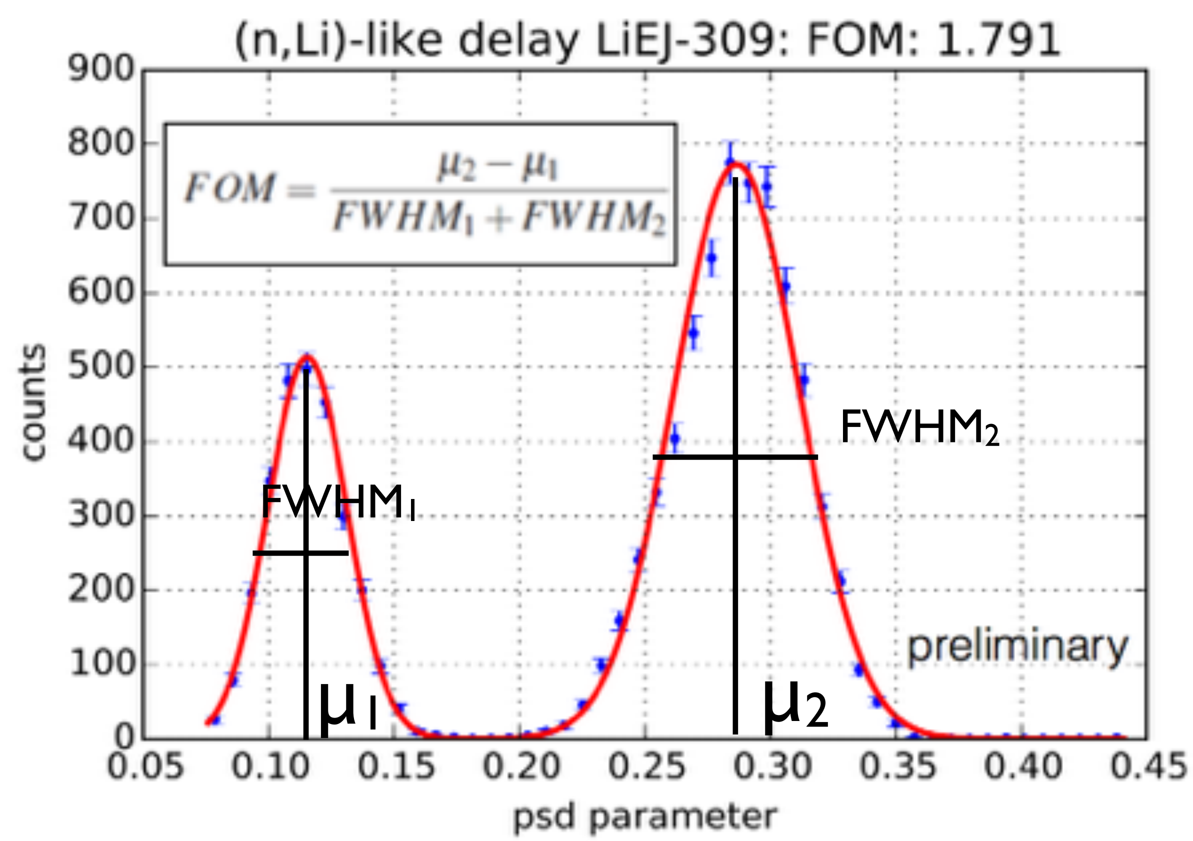


P0.2 Demonstration: Li-EJ309

- Light yield remains high for Li-EJ309
  - 8200 photons/MeV (11500 for EJ309)
  - Needed to meet resolution requirements
- PSD excellent for Li-EJ309
  - Needed for background rejection requirements



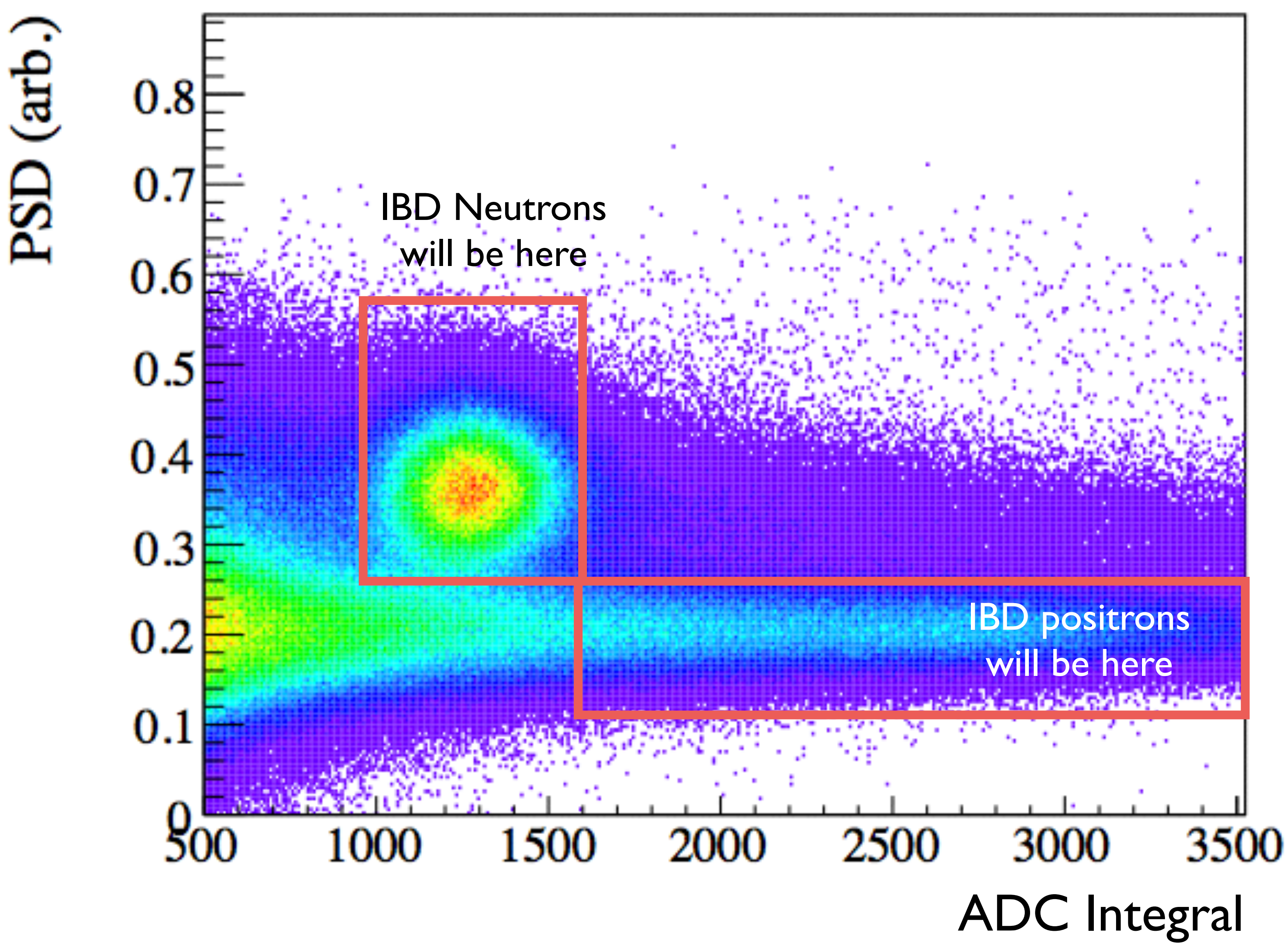




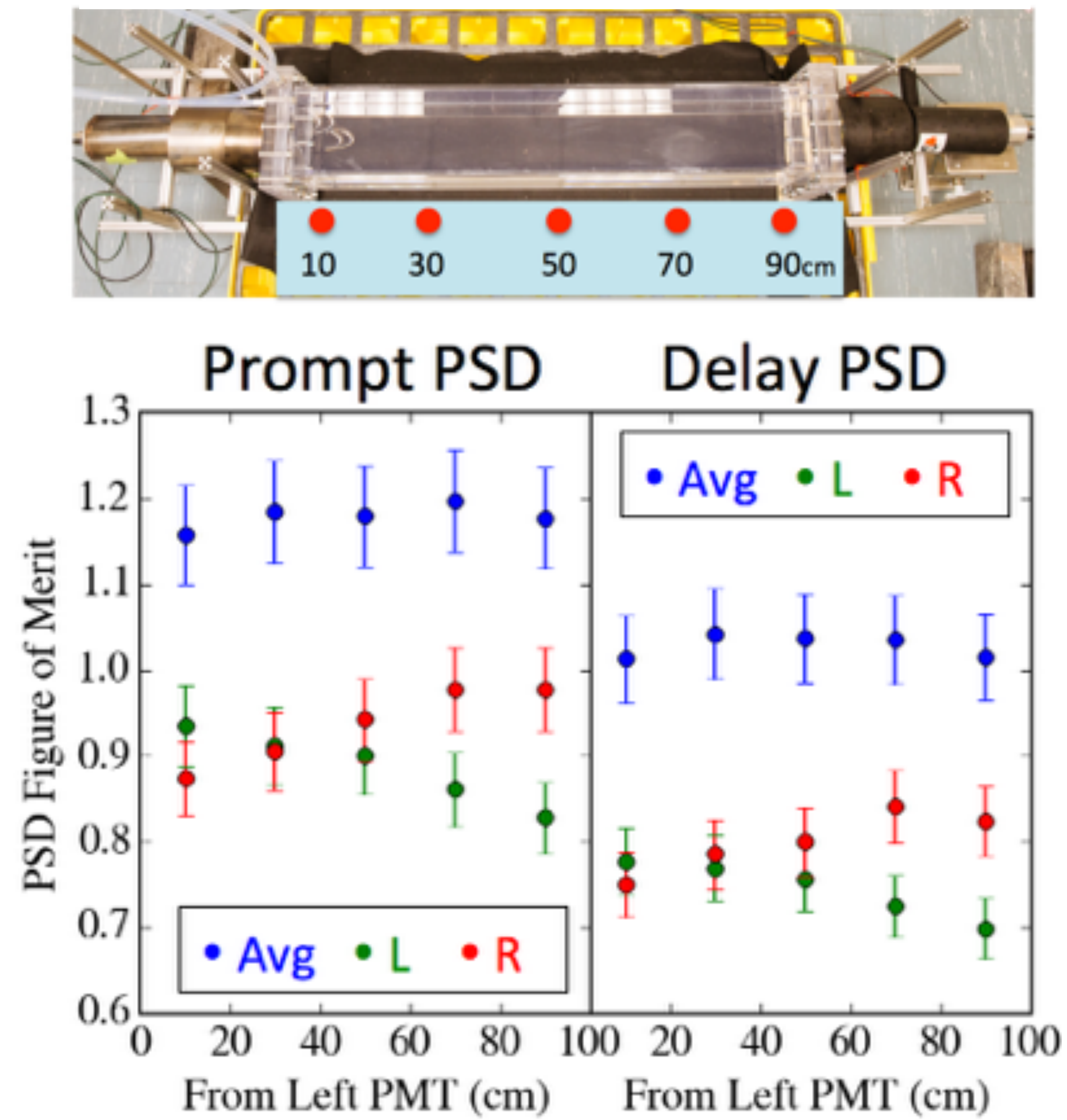
P20 Demonstration: PSD

- **PSD is maintained even at large cell sizes**
  - Ability to reject many neutron-related, reactor gamma backgrounds
  - PSD highly uniform over entirety of meter-length cell

P20, PSD Versus Energy, Reactor-Off Triggers

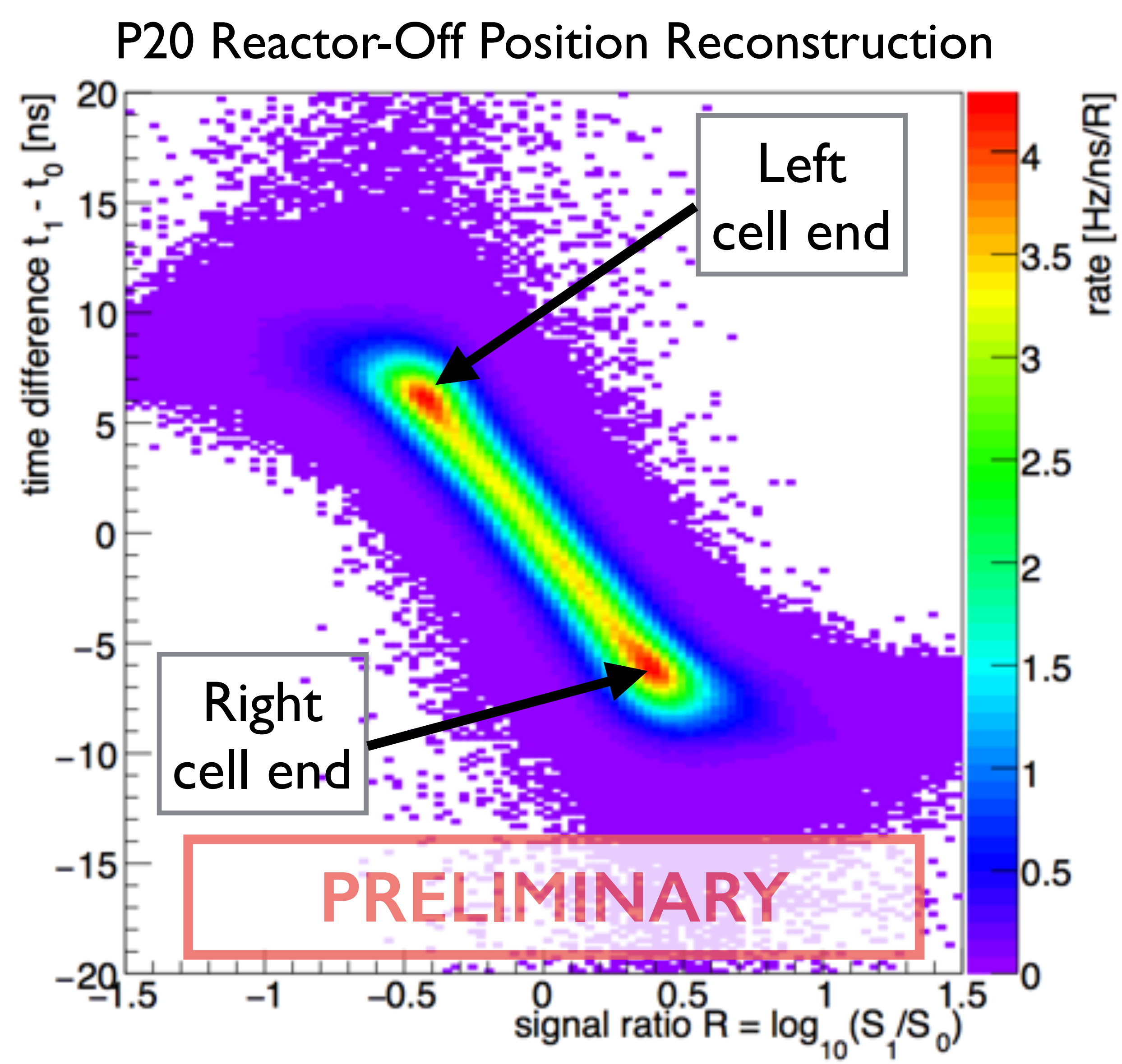


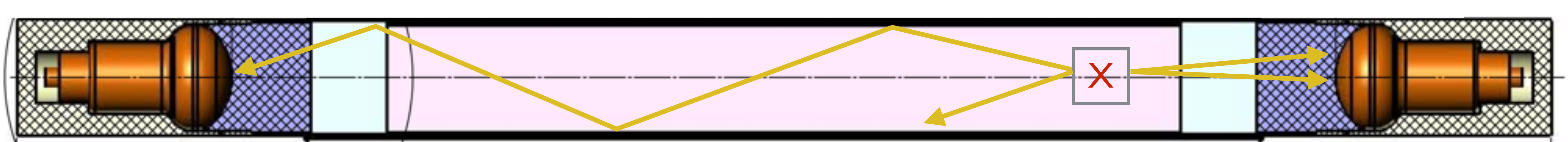
P20 PSD Response to Cf-252 source



P20 Demonstration: Topology

- Examine charge, arrival time ratios between cell's PMTs
  - Closer PMT to interaction will have more charge, shorter time
- Resolution along cell better than 10cm
  - More topology background rejection capability than we were expecting!
- Segmentation gives resolution in other two dimensions

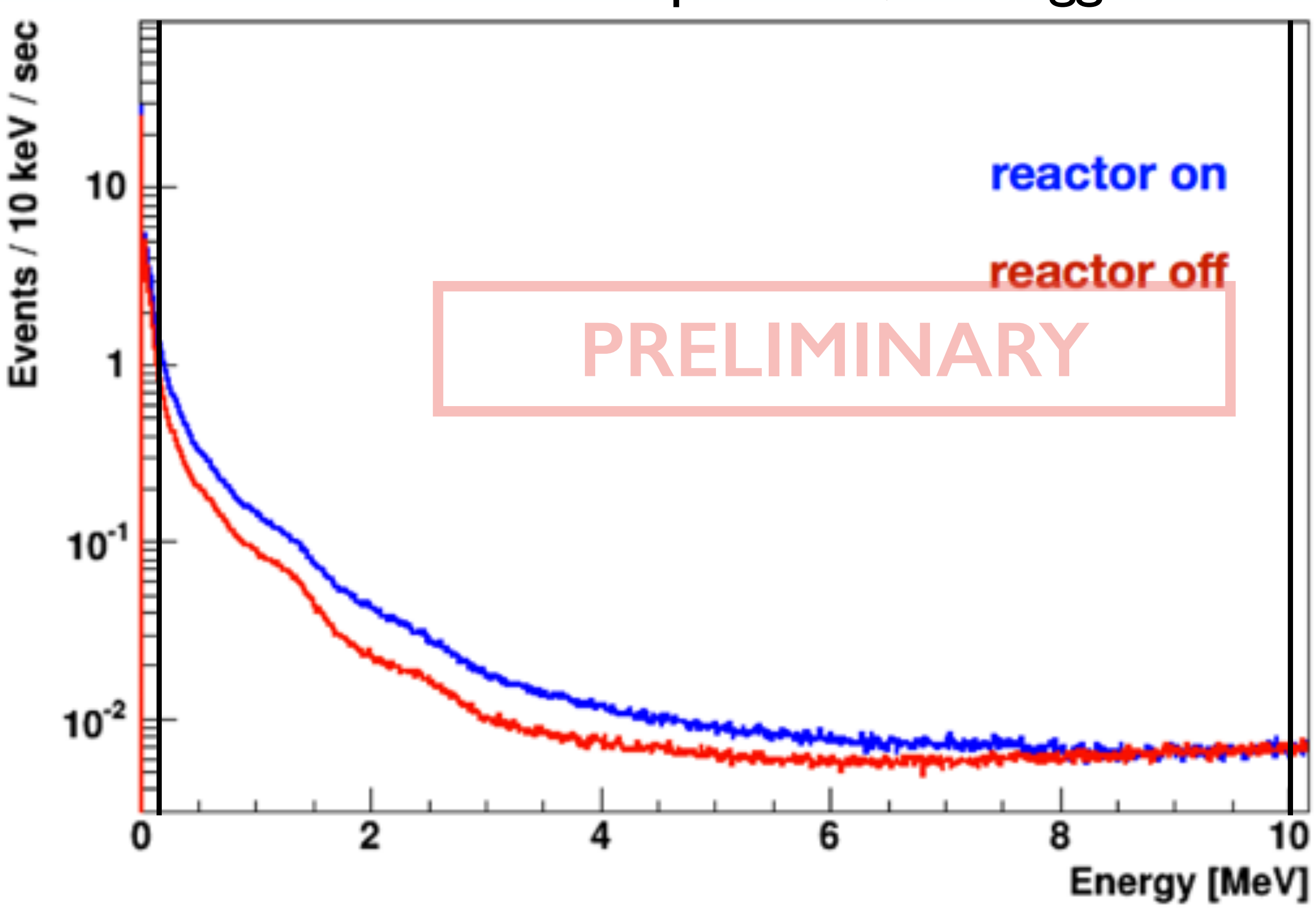




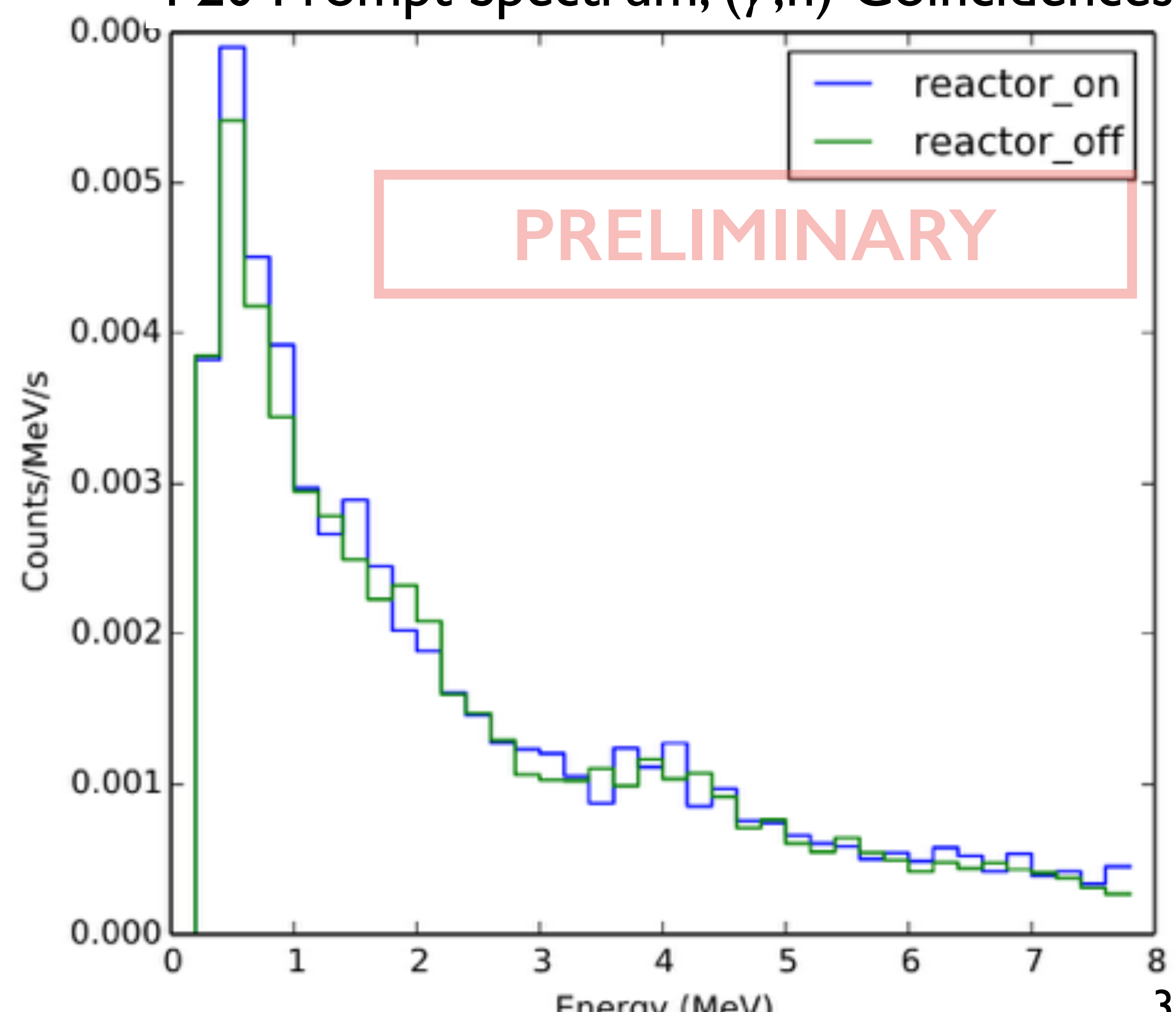
P20 Demonstration: Cosmogenics

- Sub-dominant change in raw trigger rate with reactor status
- Sub-dominant (γ,n) coincidence change with reactor status
- Reduction of cosmogenic backgrounds are primary concern!
  - Muon veto says neutrons, not muons, are primary concern!
  - Reactor-off periods very valuable!

PROSPECT20 Spectrum, All Triggers



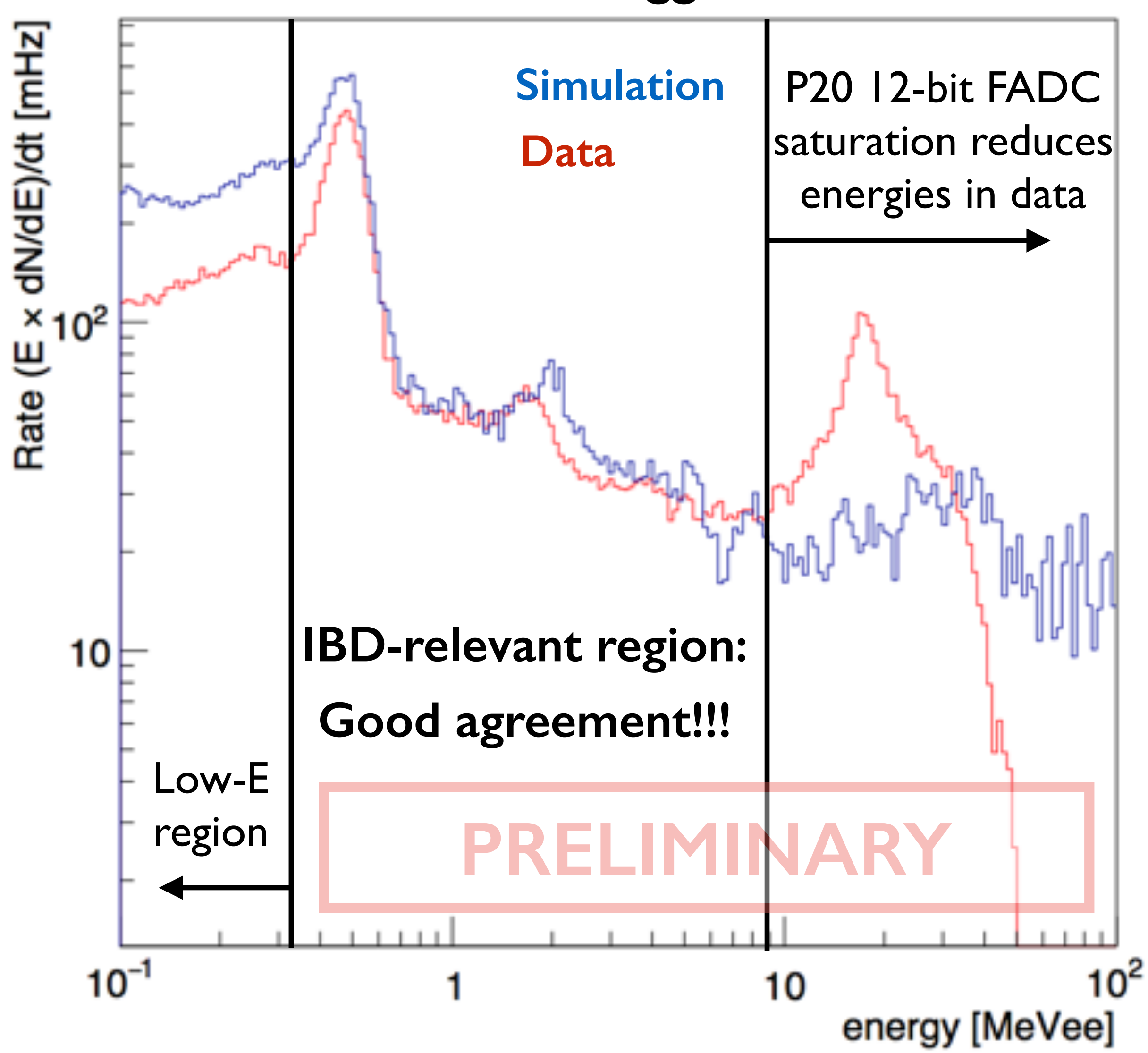
P20 Prompt Spectrum, (γ,n) Coincidences



P20 Demonstration: Sim/Data Agreement

- Have CRY- and Goldhagen-based cosmogenic neutron, muon sim
- Shows n-coincidences in good agreement with data
  - Provides confidence in modeling of full PROSPECT detector backgrounds
- Data-matched simulation will give predicted S:B for PROSPECT

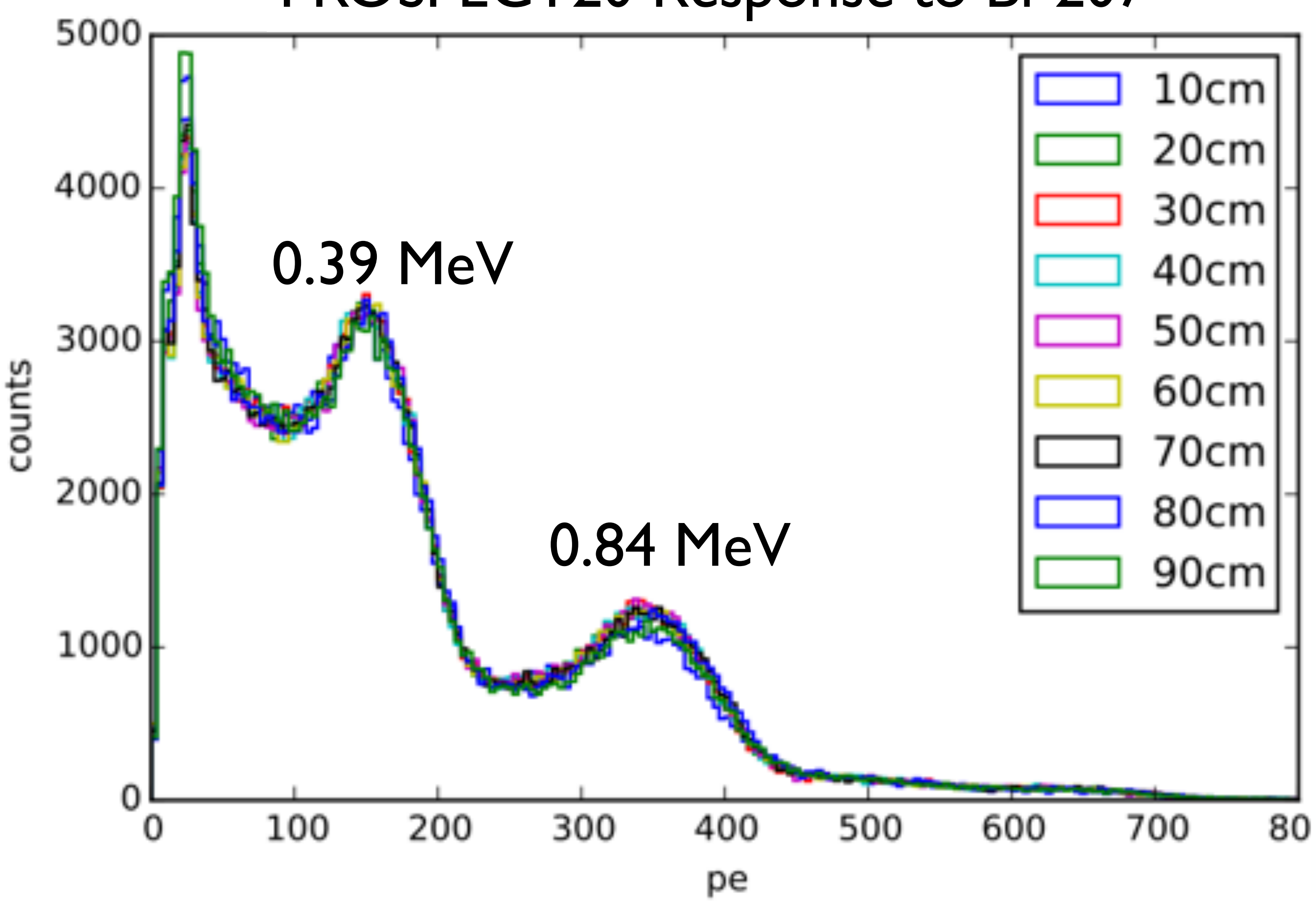
P20 n-coincident triggers, data vs. MC



P20 Demonstration: Energy Response

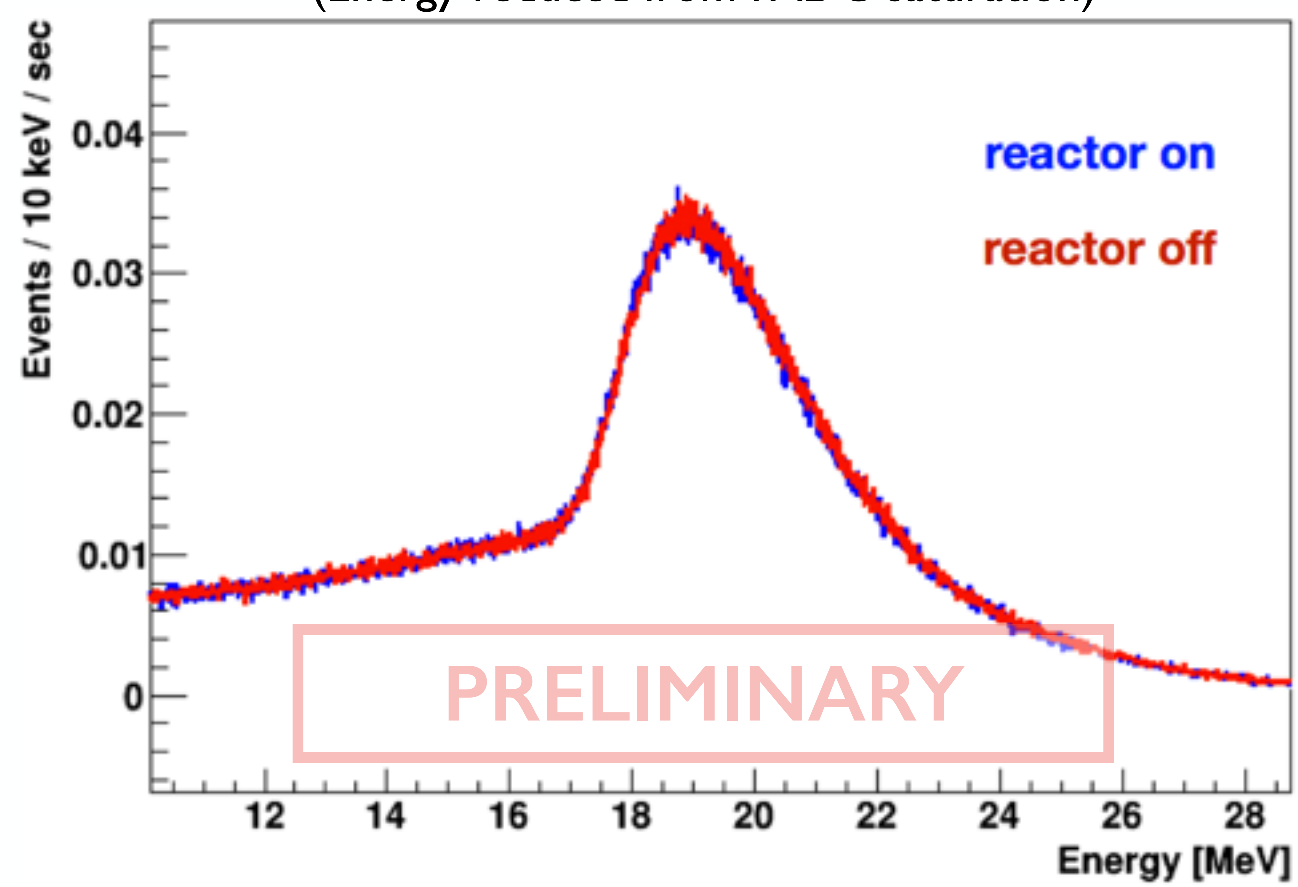
- High, uniform, and stable light collection in full cell
  - Exact PE yield is likely to be different in full PROSPECT cells
- Good energy resolution visible
  - Existing P20 PE yield is high enough to achieve 4-5% energy resolution goal
- Many background peaks, calibration sources to choose from

PROSPECT20 Response to Bi-207



Muon MIP Peak in PROSPECT20

(Energy reduced from FADC saturation)



Outline

- Intro: Reactor $\overline{\nu}_e$ Flux and Spectrum Predictions
- Reactor Anomaly and recent flux/spectrum measurements
- Future measurement of the $\overline{\nu}_e$ spectrum at PROSPECT
- Current context for PROSPECT

SBL Reactor Context

- PROSPECT: designed to provide a precision measurement for BOTH key physics goals
  - Moveable segmented detectors give best mapping of oscillation space
  - Design enables higher energy resolution other efforts
- PROSPECT has the experience, development, and infrastructure in place for the world's pre-eminent SBL reactor effort.

My (biased) overview of global efforts — Good : Not Good

	Effort	Dopant	Good X-Res	Good E-Res	L Range (meters)	Fuel	Exposure, MW*ton	Move-able?	Running at intended reactor?
US	**PROSPECT**	**Li**	**Yes**	**Yes**	**6.5-20**	**HEU**	**185**	**Yes**	**Yes**
	NuLat	Li/B	Yes	Yes	TBD	TBD	TBD	Yes	No
EU	Nucifer	Gd	No	Yes	7	HEU	56	No	Yes
	STEREO	Gd	Yes	Yes	9-11	HEU	100	No	Yes
	SoLid	Li	Yes	No	6-8	HEU	155	No	Yes
Russia	DANSS	Gd	Yes	No	9.7-12	LEU	2700	Yes	Yes
	Neutrino4	Gd	Yes	No	6-12	HEU	150	Yes	Yes
Asia	Hanaro	Li/Gd	No	Yes	20-ish	LEU	30	No	No

Sterile Oscillation Context

- PROSPECT is complimentary to current Fermilab SBN program

arxiv:1503.06637
WINP 2015

The Intermediate Neutrino Program

2.1 Sterile Neutrinos

The working group's consensus can be summarized in the following five recommendations:

3. Experiments designed to test both the ν_μ to ν_e appearance and ν_e disappearance channels are needed. We must ensure that any pion decay beam program has optimized ν_μ disappearance sensitivity.

Sterile Oscillation Context

- PROSPECT is complimentary to current Fermilab SBN program
  - Independently attacking similar suggested space for each accessible channel
  - Want (need?) signals in all channels to really trust a sterile discovery

arxiv:1503.06637
WINP 2015

The Intermediate Neutrino Program

2.1 Sterile Neutrinos

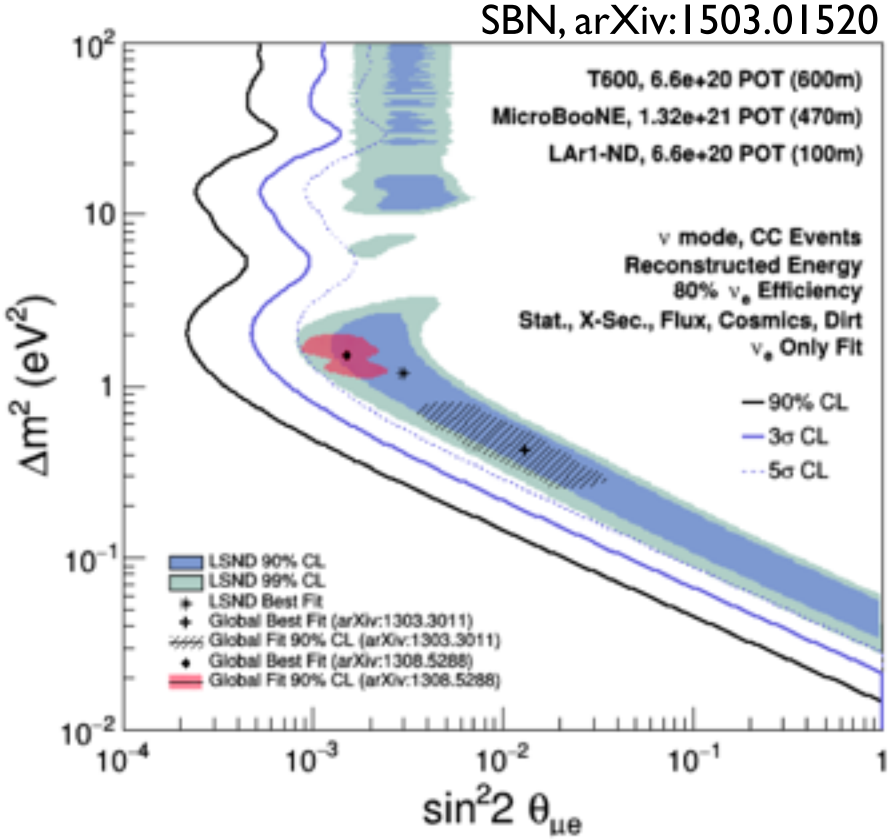
The working group's consensus can be summarized in the following five recommendations:

3. Experiments designed to test both the ν_μ to ν_e appearance and ν_e disappearance channels are needed. We must ensure that any pion decay beam program has optimized ν_μ disappearance sensitivity.

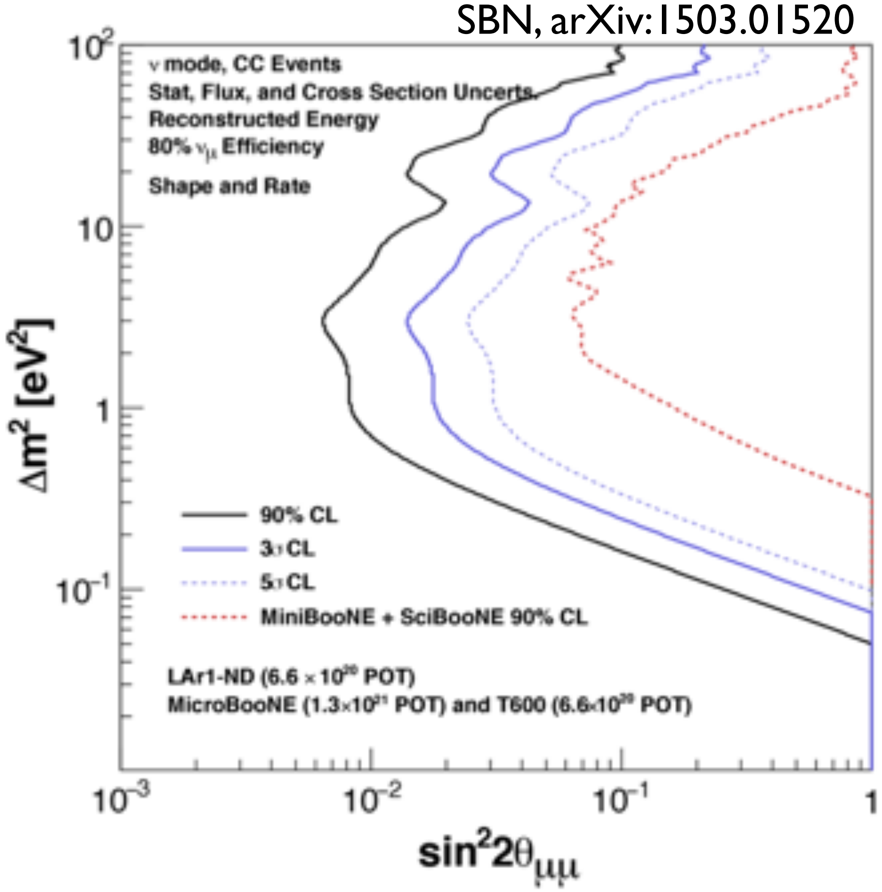
Fermilab SBN

PROSPECT

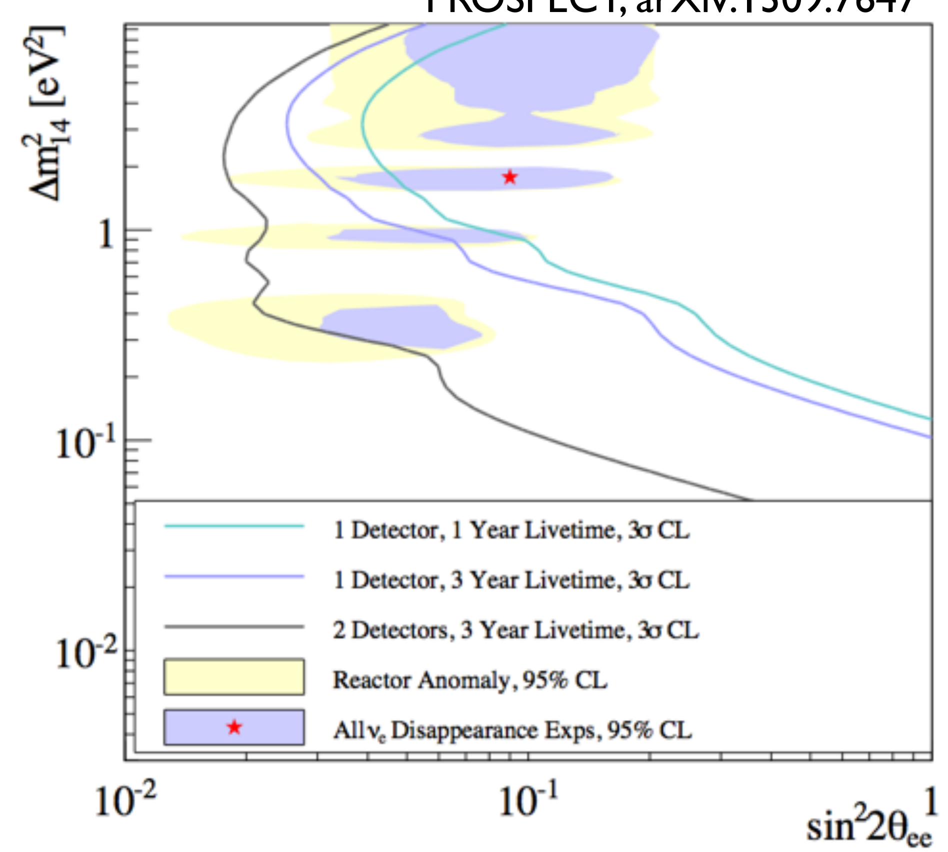
SBN, arXiv:1503.01520



SBN, arXiv:1503.01520



PROSPECT, arXiv:1309.7647



Summary

- Much has been learned about the absolute reactor $\bar{\nu}_e$ flux and spectrum in the past 2-3 years
- More data is needed to address persisting questions
- PROSPECT will provide valuable new SBL ^{235}U $\bar{\nu}_e$ data
  - Can address existing sterile best-fits with <1 calendar year of data
  - Reactor $\bar{\nu}_e$ disappearance complimentary to SBN program (ν_e app, ν_μ dis)
  - Learn much about reactor spectrum regardless of oscillation outcome
- Prototype deployments at HFIR are underway
  - Months of data already demonstrate unique position resolution, energy resolution, and background rejection capabilities
  - Well-prepared for efficient assembly and deployment of the full experiment

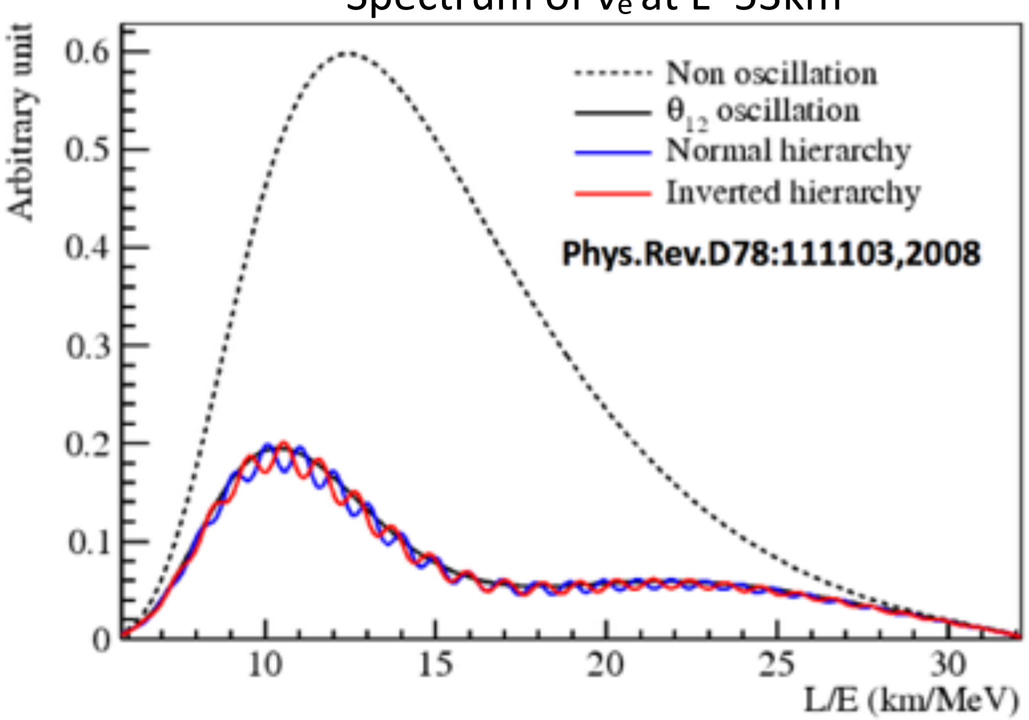
END

Reactor Spectrum: Why Do We Care?

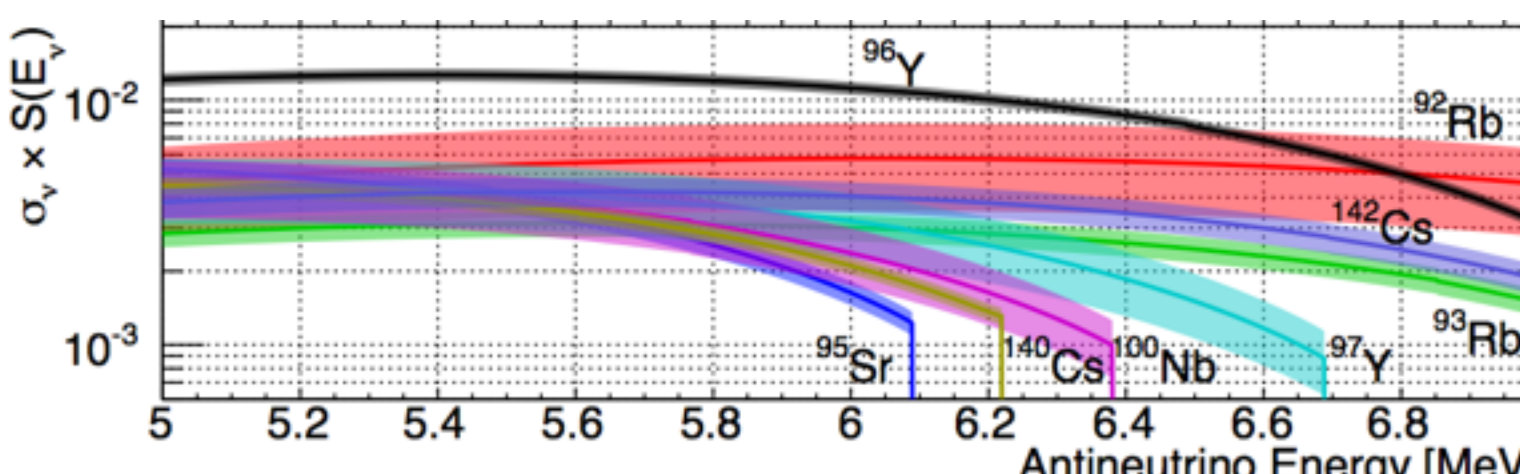
- Major implications for Standard Model if ν_s DO actually exist
- Even if they do not, ability to constrain reactor $\bar{\nu}_e$ models
  - Valuable for reactor oscillation experiments
  - Inputs to reactor modeling
  - 'Reactor spectroscopy:' probe individual branches in reactor spectrum
  - Implications for non-proliferation

Buttons Provided by Neutrino2014!
Sweater Provided by J. Asaadi

Spectrum of ν_e at L~53km

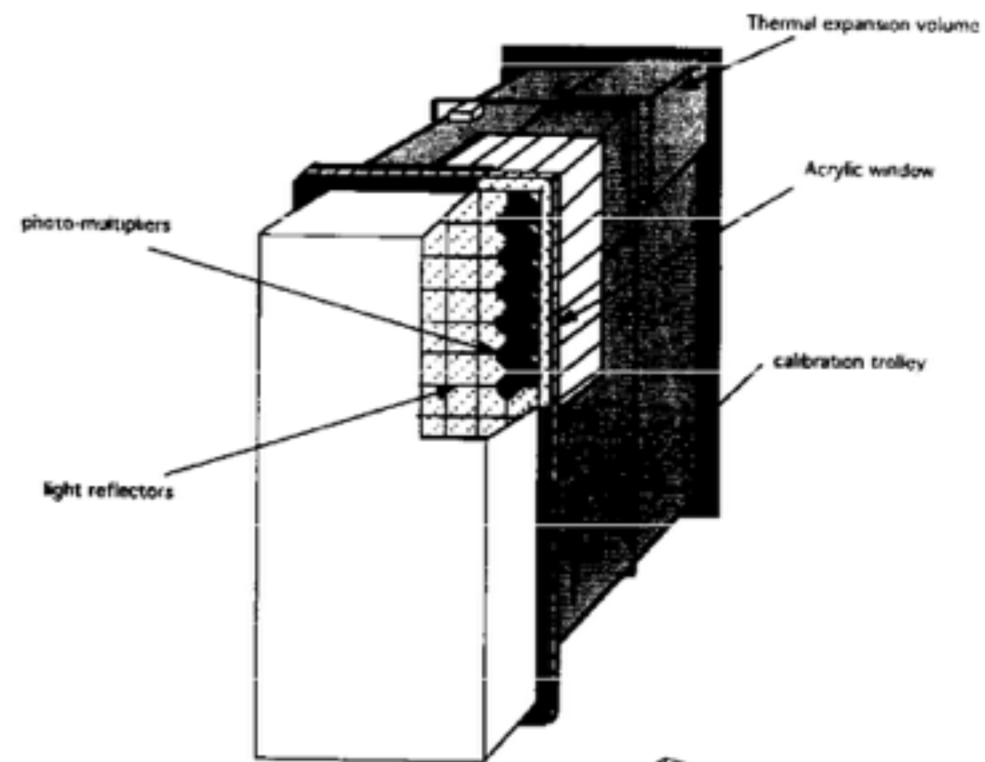


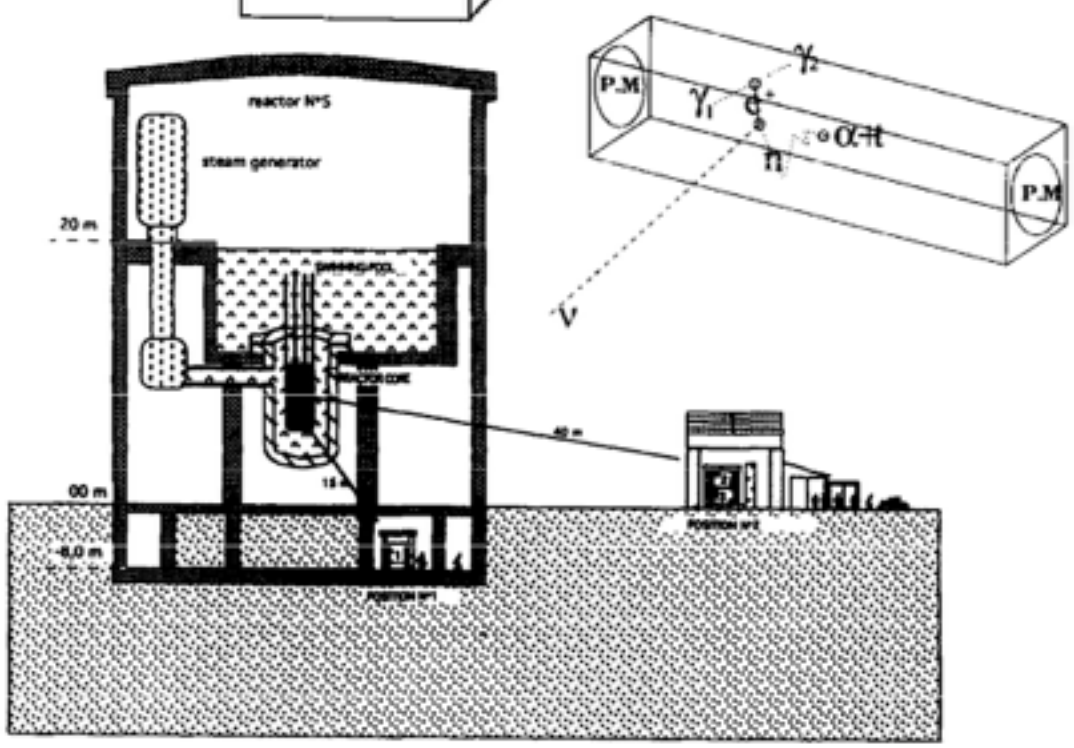
Dwyer and Langford, PRL 114 (2015)



Historical Context

- A similar experimental setup in the past: Bugey-3
  - Segmented short-baseline LiLS detector
- PROSPECT Pros:
  - Smaller reactor core, closer to core: better for SBL oscillation search
    - Further improved by cell-to-cell oscillation search
  - Stable scintillator: Bugey's degraded after a few months in near detector!
  - Smaller target dead volume: ~2% versus >15% for Bugey
  - Better light yield, energy resolution
- Only Bugey Pro: Overburden
  - 14+ mwe (Bugey-3), <10 mwe (PROSPECT)
    - Bugey had 25:1 S:B; PROSPECT can be successful with 1:1



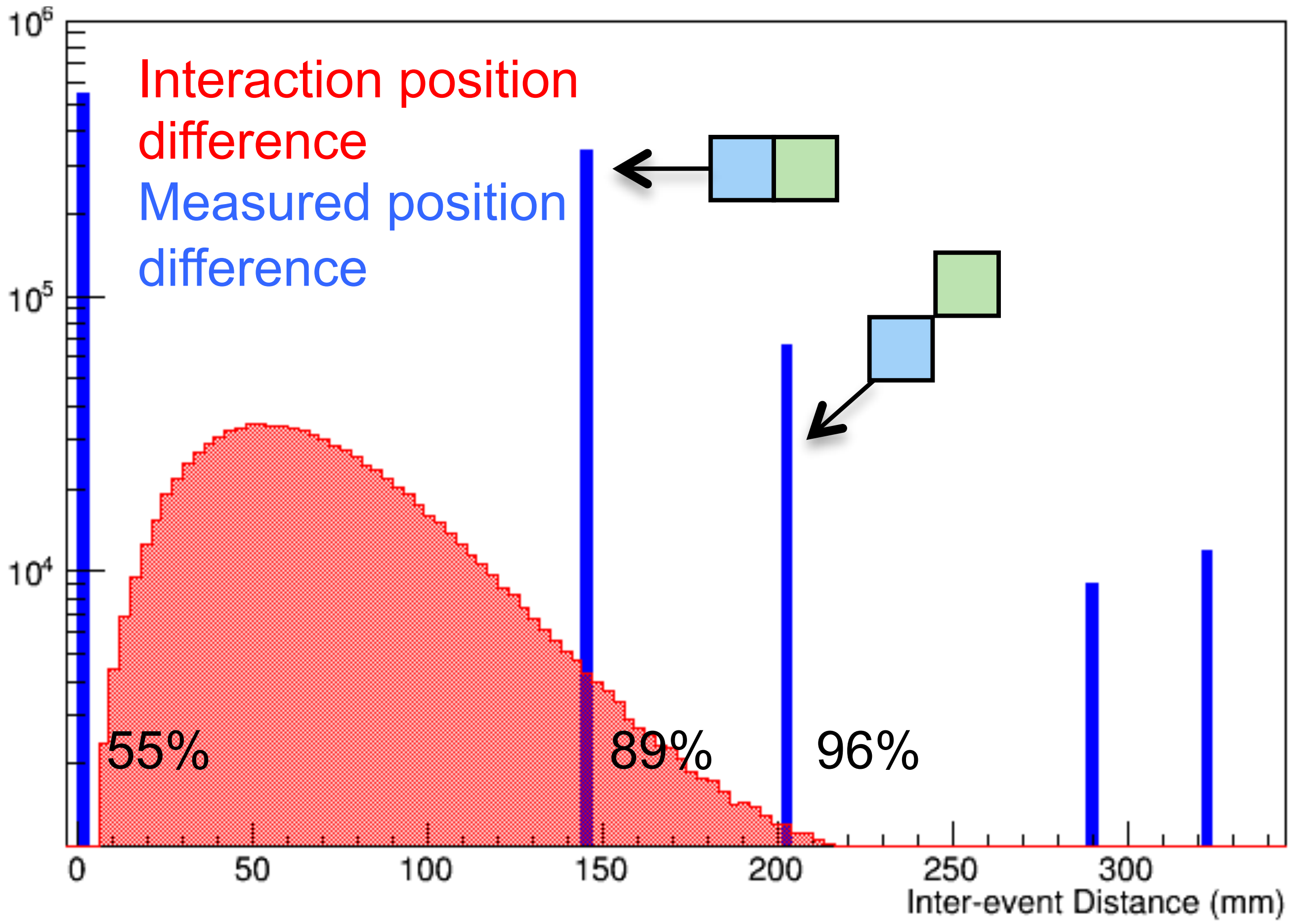


from Abbes at al, NIM **A**374 (1996)

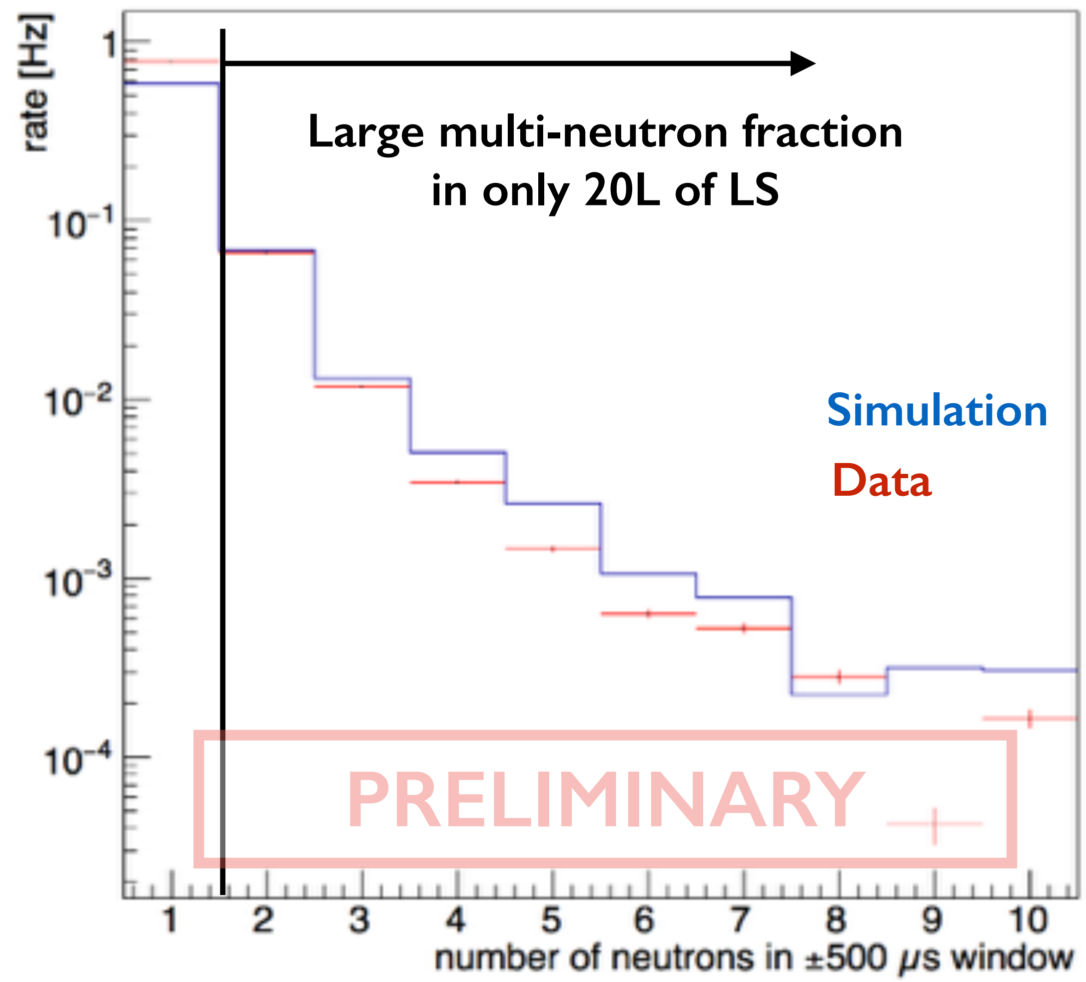
Full Simulation Background Estimates

- Have CRY- and Goldhagen-based cosmogenic neutron, muon sim
- Data-matched simulation will give predicted S:B for PROSPECT
  - Data/MC match already very good for PROSPECT20
  - MC predicts major bkg reductions from topology and trigger multiplicity

P2000 MC: IBD Position Coincidence Distribution

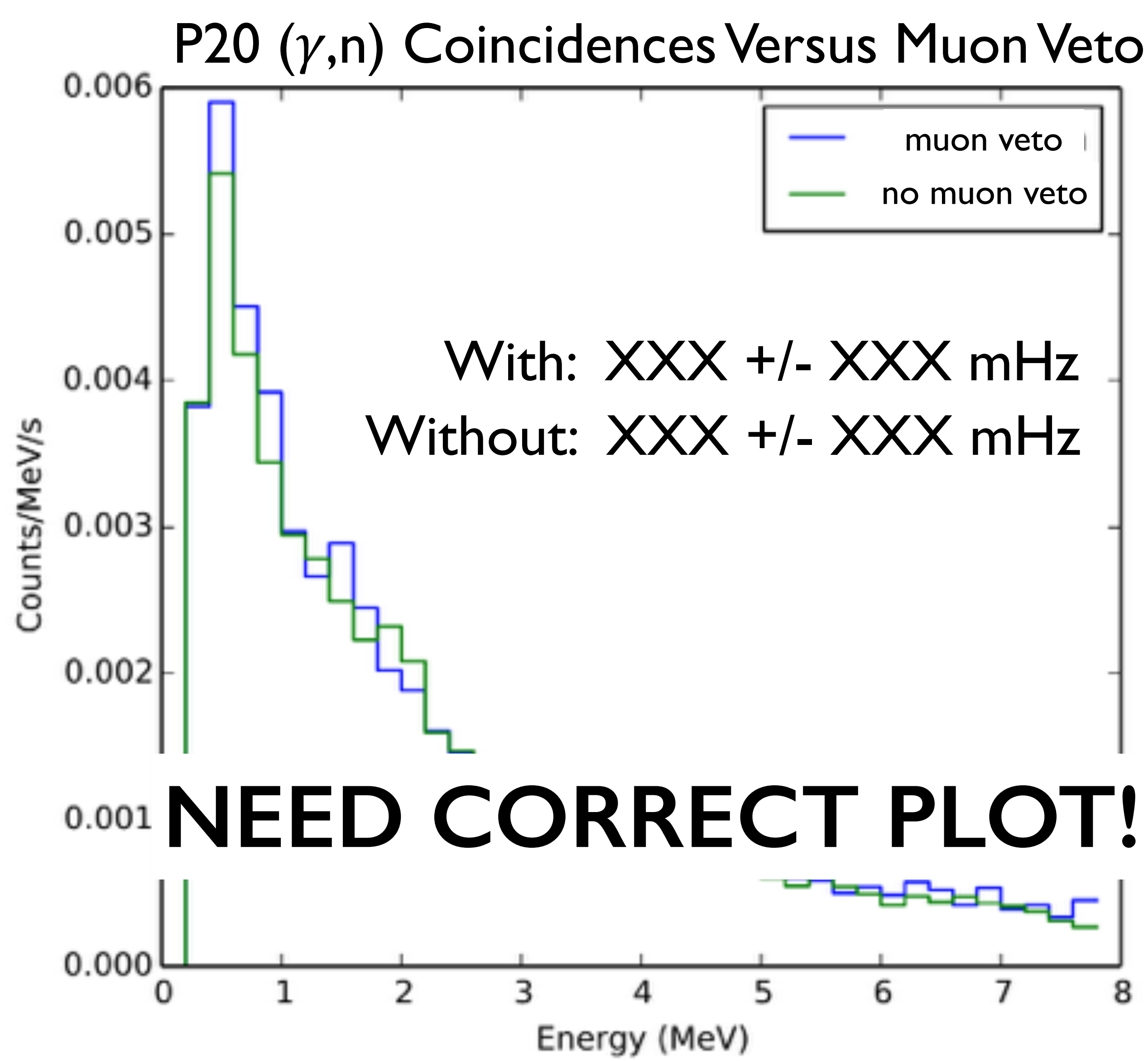


P20: Time-correlated neutron-like triggers



P20 Demonstration: Neutrons

- Sub-dominant changes in (γ,n) coincidence with muon veto
- Fast or multiple cosmogenic neutrons provide main background
  - Thus our PSD is extremely important
  - Position reconstruction also important to reject multi-neutron events

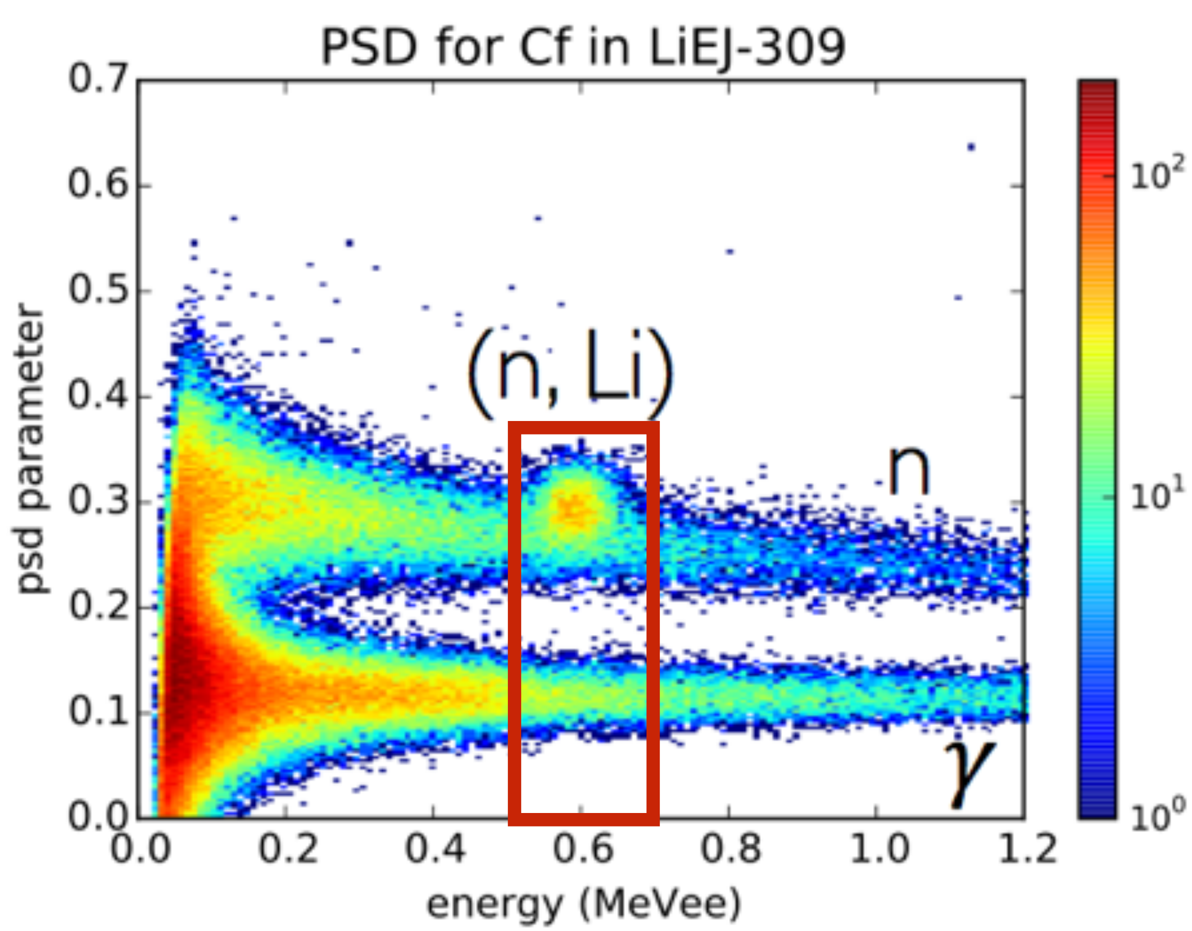


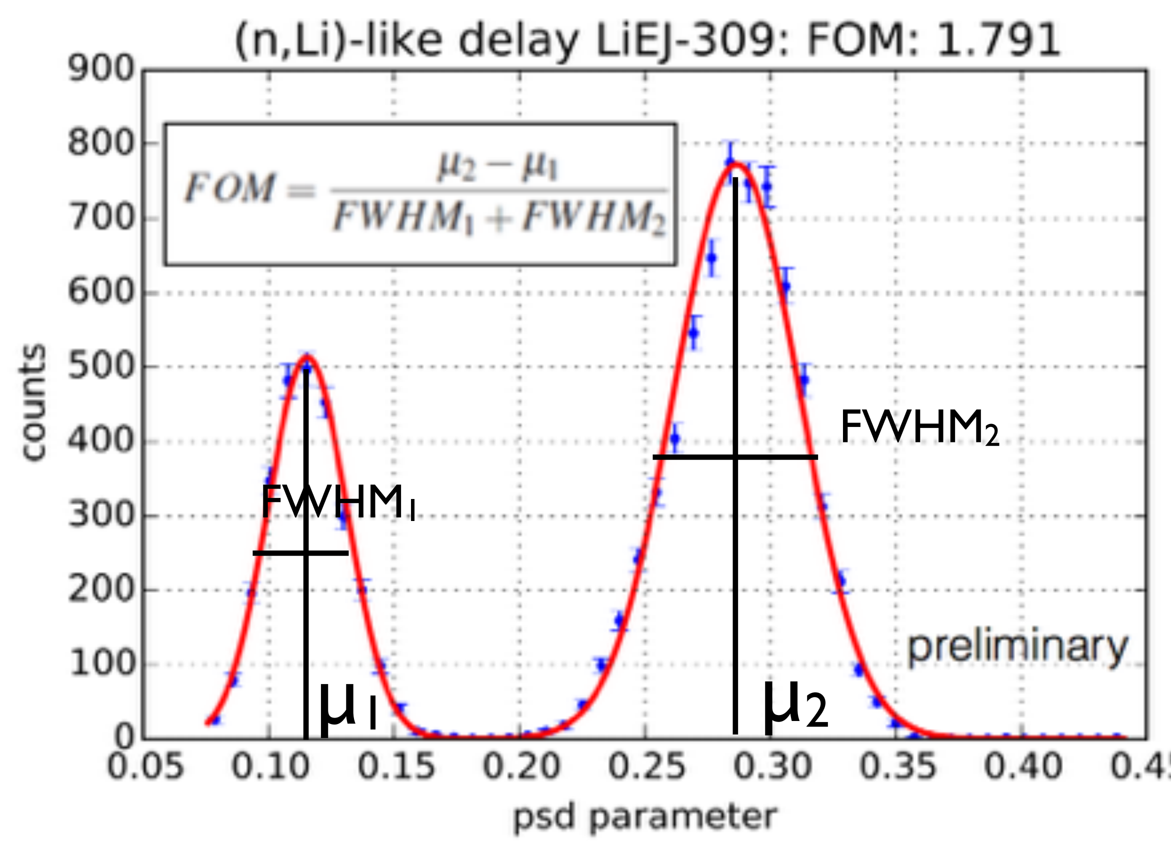
P0.2 Demonstration: LiLS

- PSD excellent for Li-doped EJ-309

For FOM =1, PSD cuts

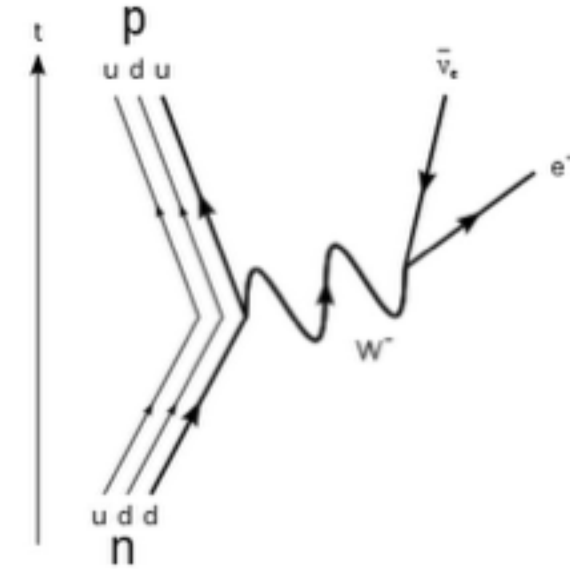
- Background rejection: 99%; signal: 99%
- Background rejection: 99.9%; signal: 90%





Beta Decay Recap

- W-mediated weak interaction
- Use Fermi's Golden rule to calculate:

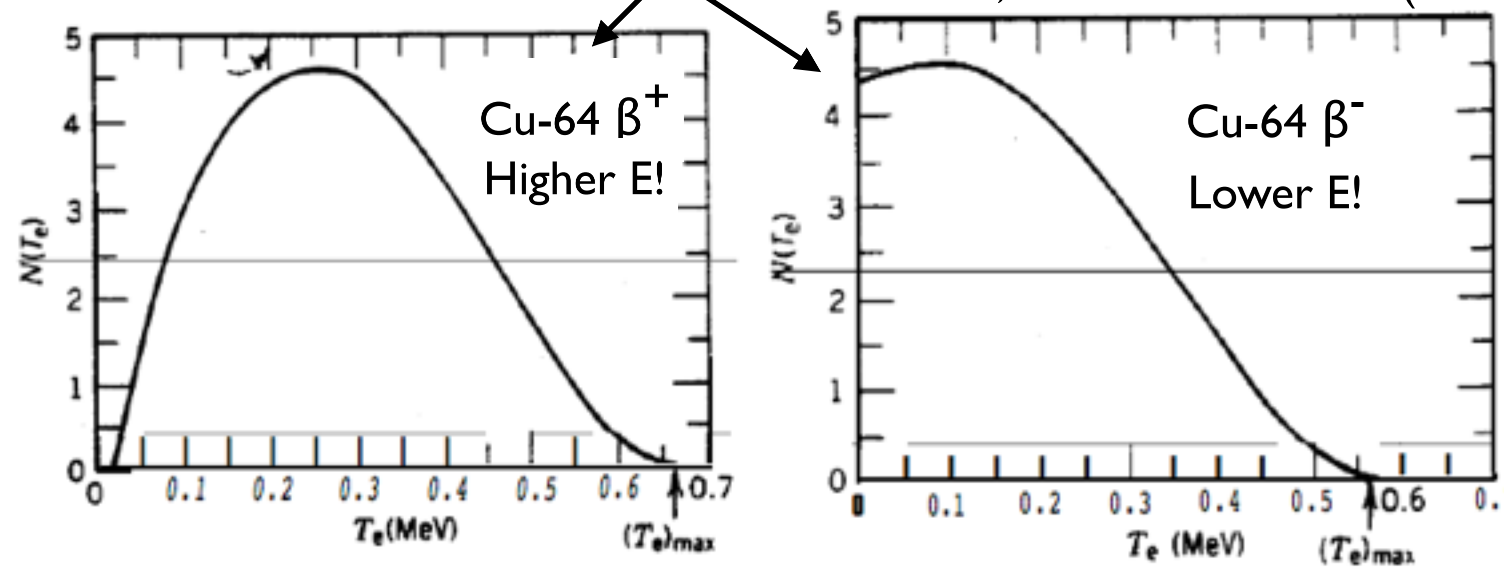


$$N_\beta(W) = K\, \underbrace{p^2(W - W_0)^2}_{\text{phase space}}\, F(Z, W)$$

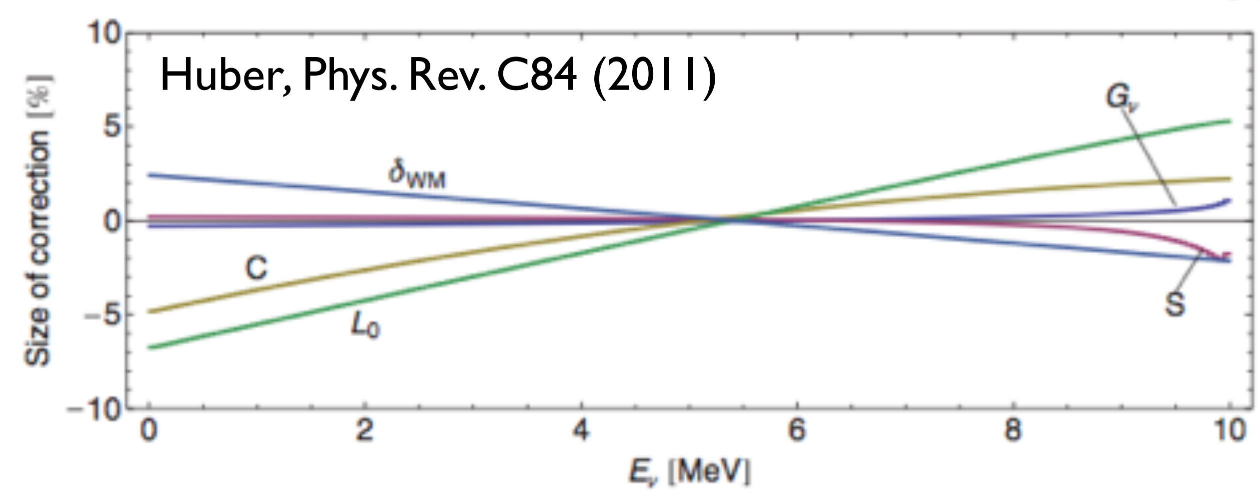
From nuclear matrix element:
Extra factors of p pop
in here for beta decays

QED correction: semi-classicaly,
positive nucleus attracts
product beta; lowers its energy

RD Evans, *The Atomic Nucleus* (1955)



- Other corrections:
  - Finite size: C, L_0
  - Electron screening: S
  - Radiative corrections: C
  - Weak magnetism: d_{wm}



Forbidden Decay Handling

- W-mediated weak interaction
- Use Fermi's Golden rule to calculate

$$N_\beta(W) = K\, \underbrace{p^2(W - W_0)^2}_{\text{phase space}}\; F(Z, W)$$

From nuclear matrix element:
Extra factors of p pop
in here for beta decays

- Hayes, et. al, PRL 112 (2014): conversion result highly dependent on forbidden-ness of virtual branches
  - Capable of shifting predicted flux downward by 5%
  - Has not been shown what forbidden decay treatment would reproduce both reactor beta and nuebar spectra — but it might be possible to do so

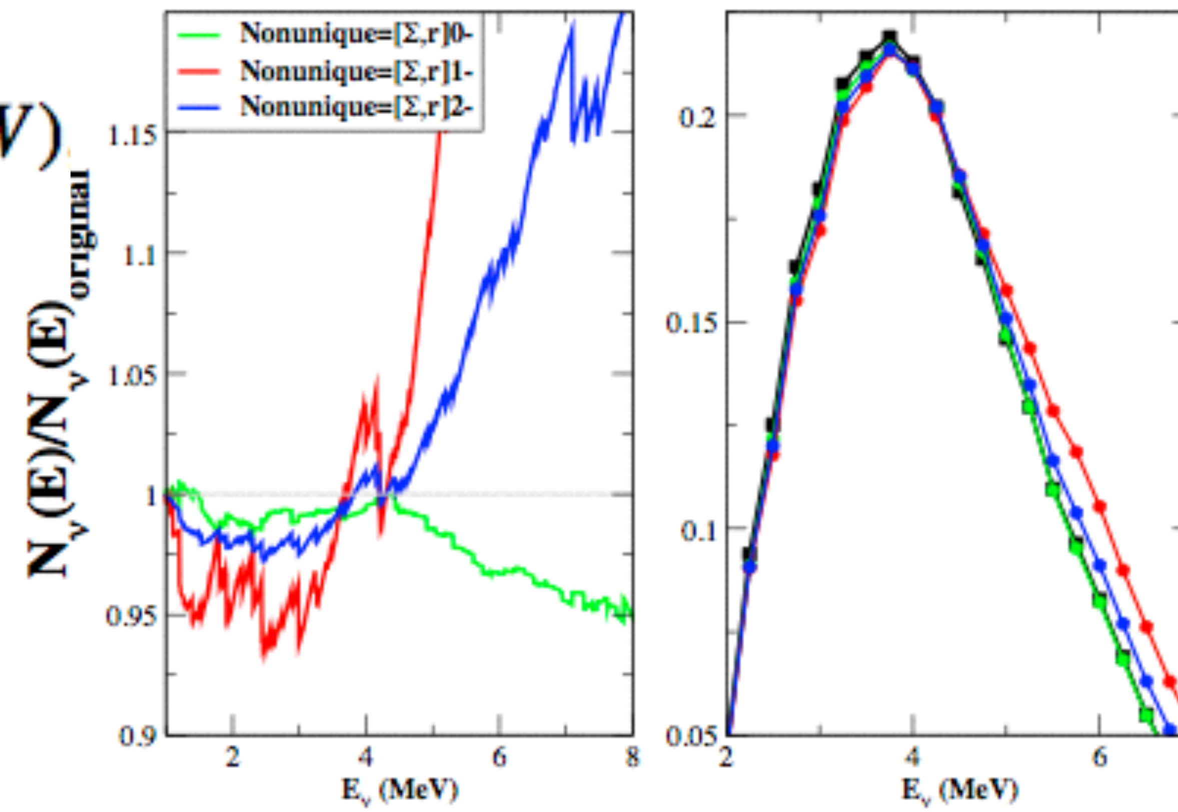
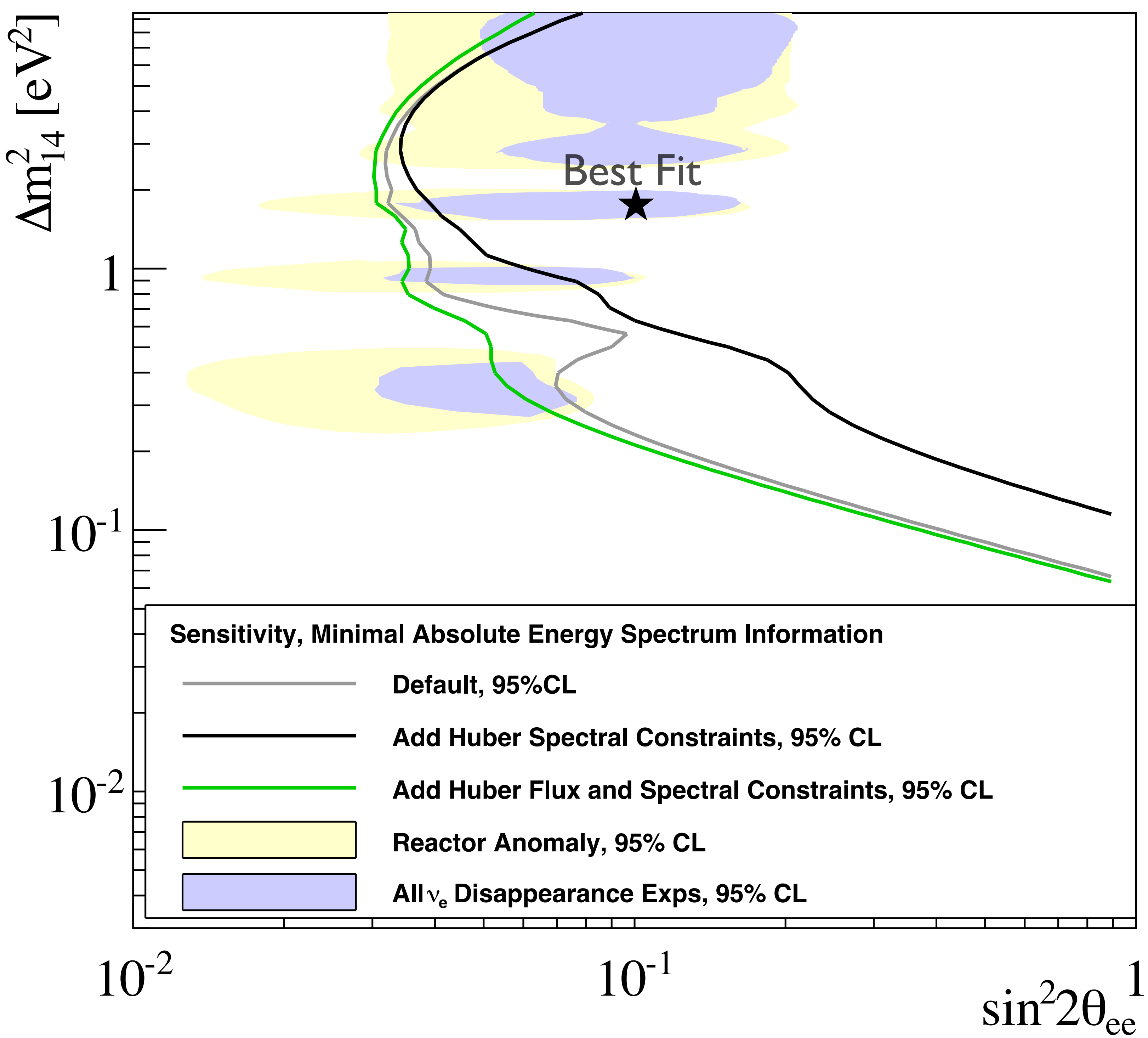


FIG. 3: Different treatments of the forbidden GT transitions contributing to the antineutrino spectrum summed over all actinides in the fission burn in mid-cycle [21] of a typical reactor. The left panel shows the ratio of these antineutrino spectra relative to that using the assumptions of Ref. [4]. The right panel shows the spectra weighted by the detection cross section, where the additional curve in black uses the assumptions of Ref. [4]. The spectra are strongly distorted by the forbidden operators, being lower below the peak and in some cases more than 20% larger above the peak than Ref. [4]. The corresponding change in the number of detectable antineutrinos relative to [4] is -0.75%, 5.8% and 1.85% for the 0^-, 1^-, and 2^- forbidden operators, respectively.

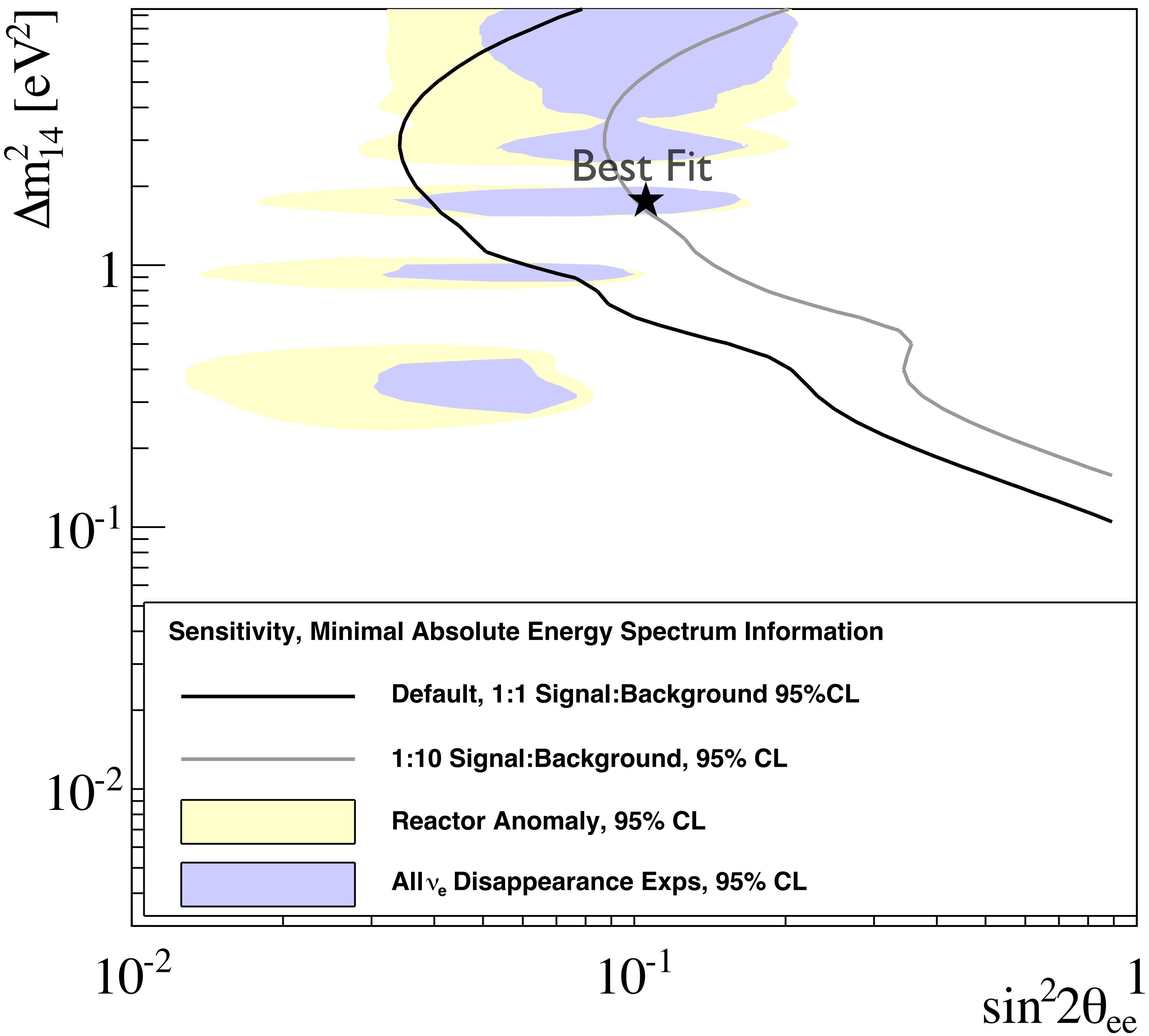
Oscillation: Absolute Uncertainties

- Oscillations with spectral prediction assumptions included:



Oscillation: S:B

- Still have significant osc. sensitivity with 10x larger background



Efficiencies

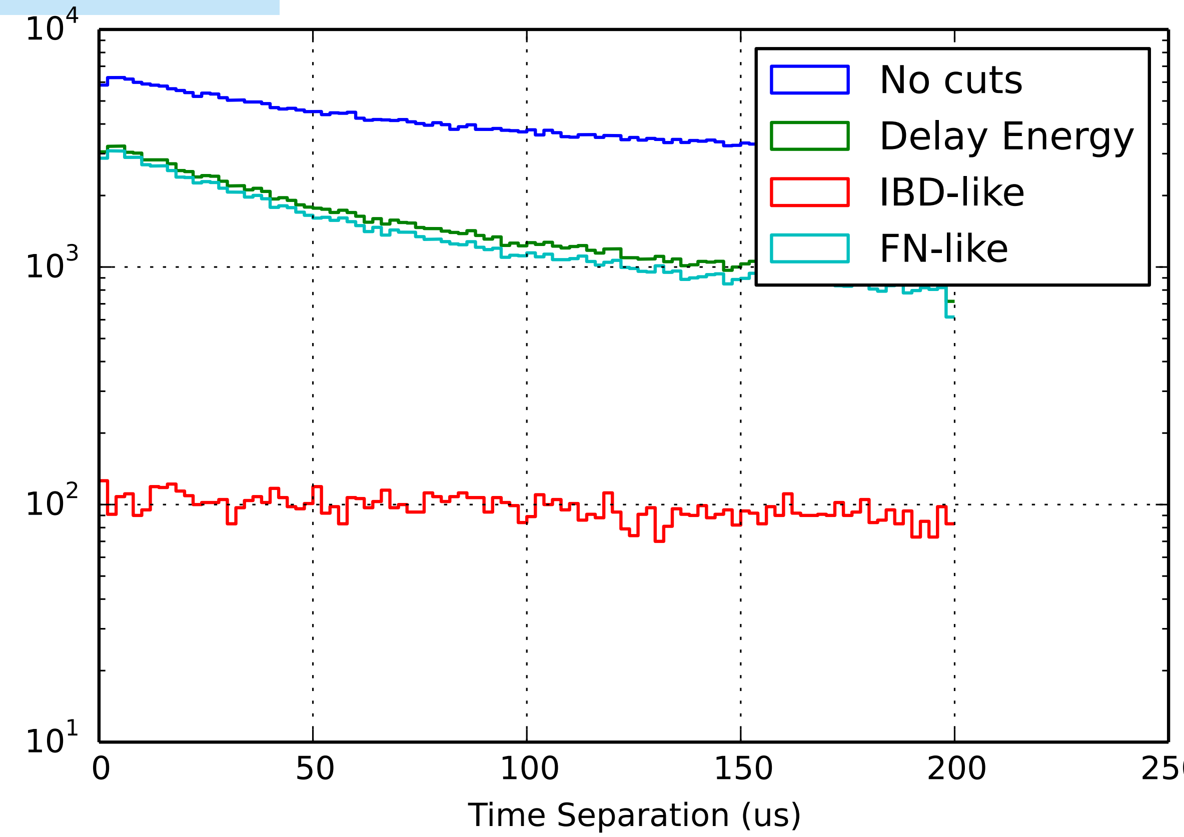
- Unlike some other SBL detectors, efficiency should be good
- Trigger: ~100%
- Energy Cuts:
  - PROSPECT0.2: Delayed energy cut efficiency can be high: 80+% after reduction from nLi capture ratio (~85%) (Property of Li-LS)
  - Simulations: 2MeV cut gives 80+% efficiency
- PSD Cuts
  - PROSPECT0.2: Can be very high efficiency for both prompt and delayed: 90+%
- Muon veto cuts
  - ~400 Hz muons in detector: 100 microsecond veto gives 96% non-vetoed data
- Time coincidence / Multiplicity (2 in coincidence only)
  - Need simulations to determine spill-in/out/reflecting neutron events: 75+%, surely…
- Topology:
  - Simulations: nearest-neighbor coincidence cut: 95+% efficiency
  - Delayed position topo cut (single cell for nLi): ~100% efficiency (Property of Li-LS)

Relative Systematics

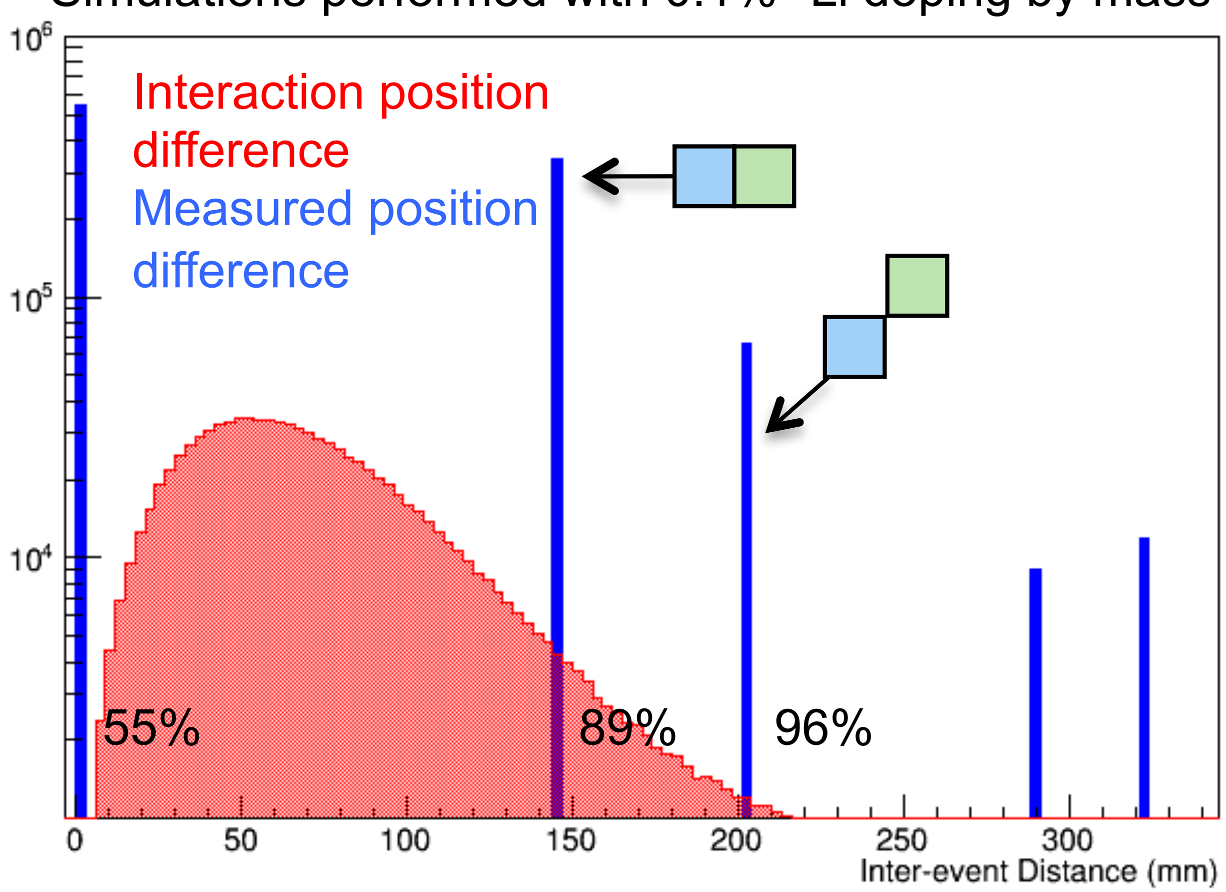
- Osc sensitivities include 1.5% totally uncorrelated uncertainty
- Developing covariance matrix approach to include relative cell-to-cell detector, backgrounds systematics more precisely
- Running simulations to quantify cell-to-cell energy response differences
  - How does calibration source signal differ with deployment position?
  - How much is from energy leakage?
  - How much is from as-constructed cell-to-cell variations?
  - How big a cell-to-cell response correction will we need to apply? Uncertainties on this correction?

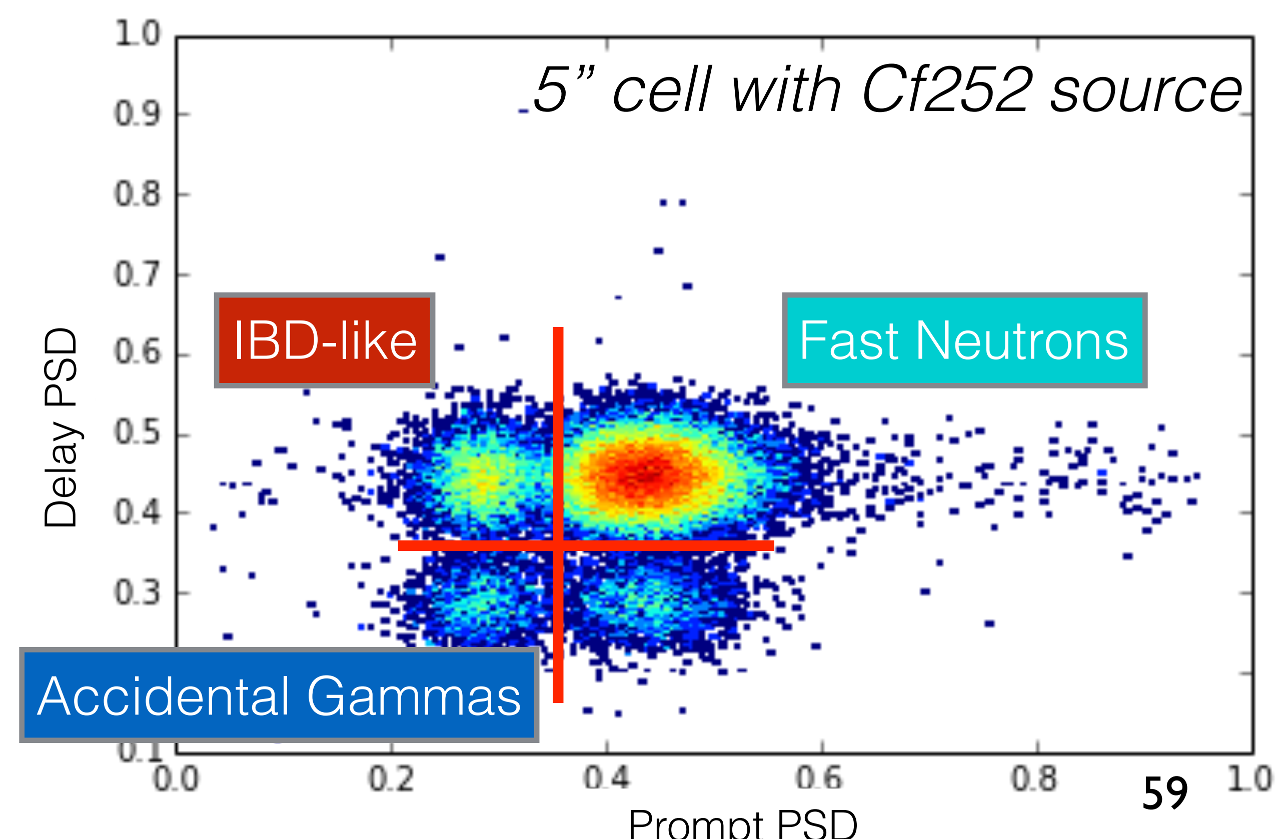
Background Reduction: Coincidences

- Major reduction from different sources:
  - Delay energy + PSD: >50x
  - Topology coincidence: >10x
  - Consider higher E_{prompt} cut: 2 MeV
  - Heavier loading, shorter coincidence window: reduction of muon veto time, accidental coincidences



Simulations performed with 0.1% ^{6}Li doping by mass

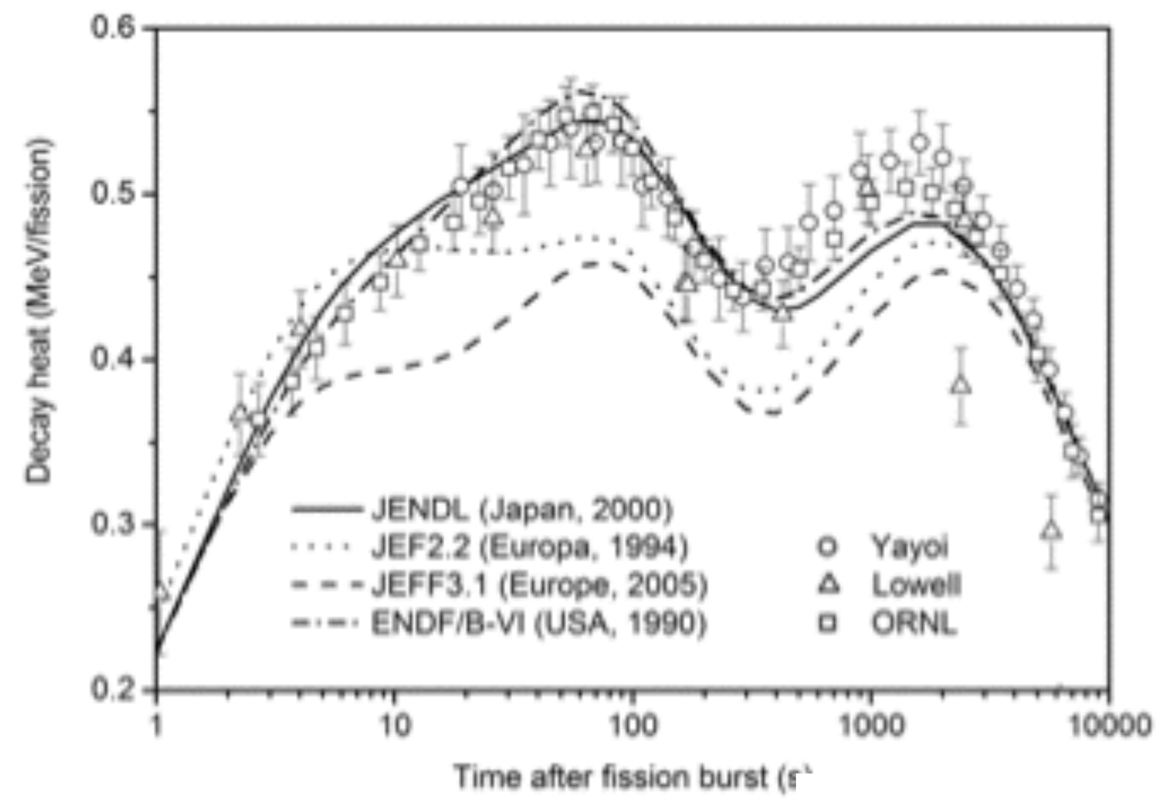




Reactor Spectroscopy: Application

- Why is there more decay heat than predicted 3-3000s after a reactor is turned off???
- Means we need higher cooling safety factors during reactor-off periods: This costs $$$!!!
- Hypothesis: maybe we measured branching fractions of some rare isotopes incorrectly…

Figure 3. Electromagnetic decay heat following thermal fission burst of ^{239}Pu – data from JENDL, JEF-2.2, JEFF-3.1 and ENDF/B-VI are shown together with experimental data from Yayoi, Lowell and Oak Ridge National Laboratory



Nuclear Science
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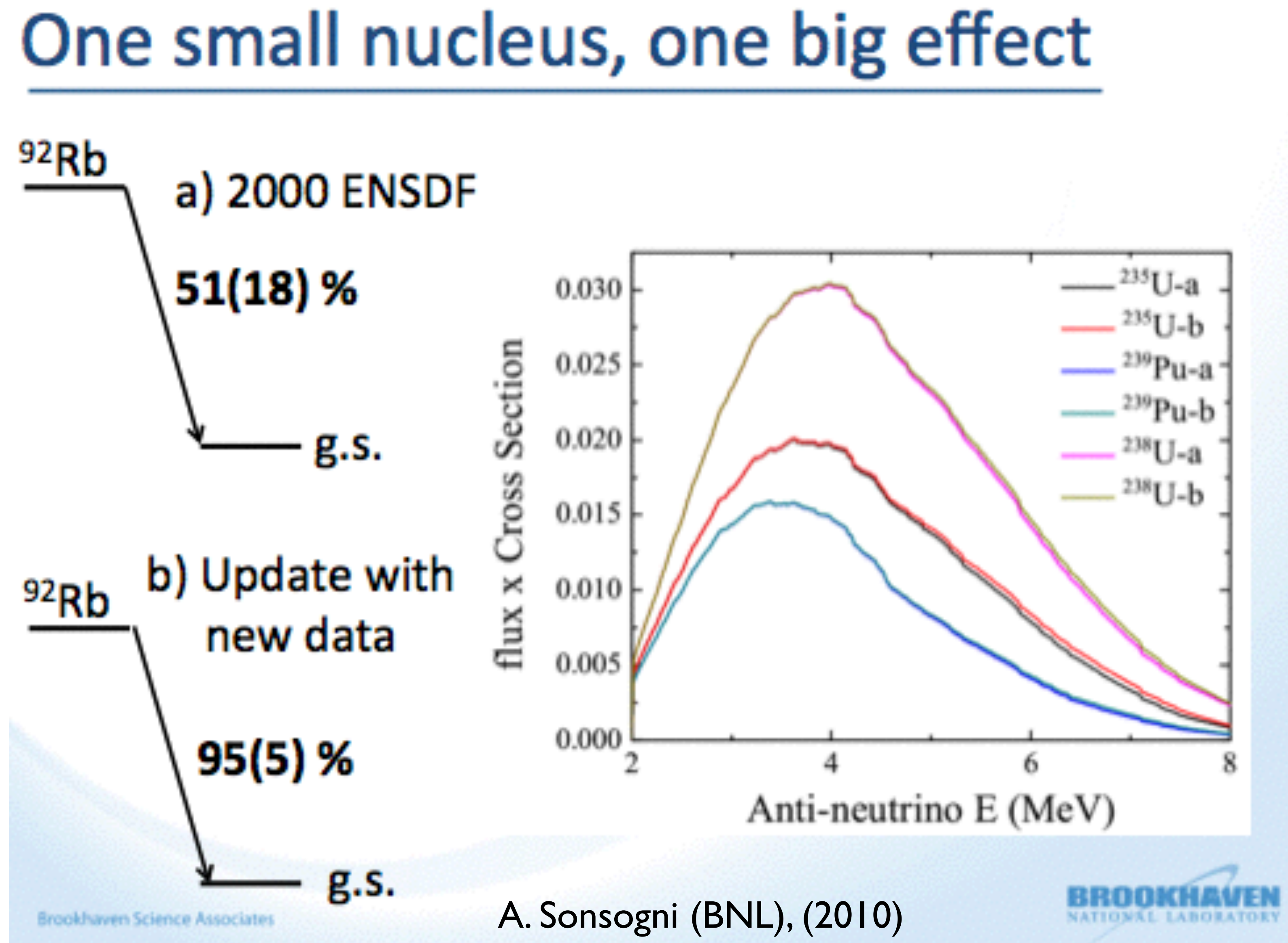
VOLUME 25

ASSESSMENT OF FISSION PRODUCT DECAY DATA FOR DECAY HEAT CALCULATIONS

Reactor Spectroscopy: Example

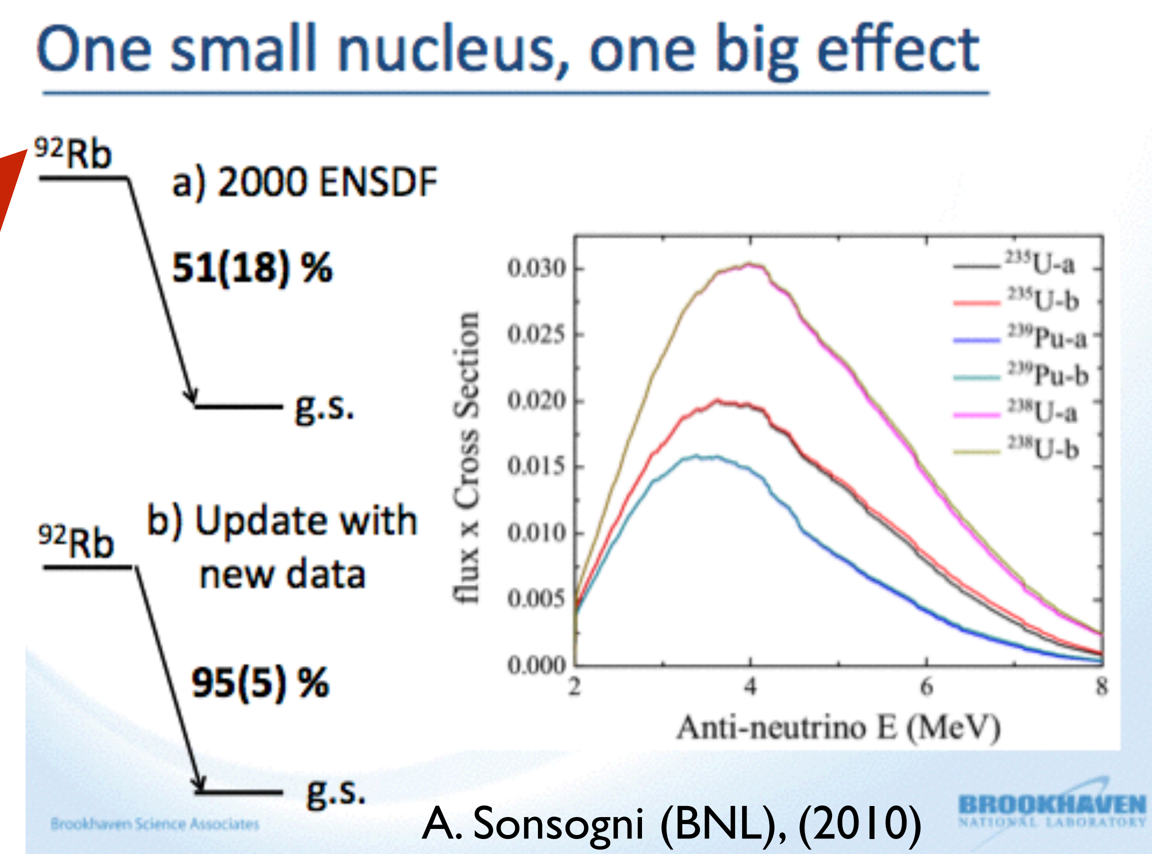
- TAGS:
  Total absorption gamma spectroscopy
- Measure total gamma energy, not individual gamma energies
- Allows ID of levels, BRs much easier

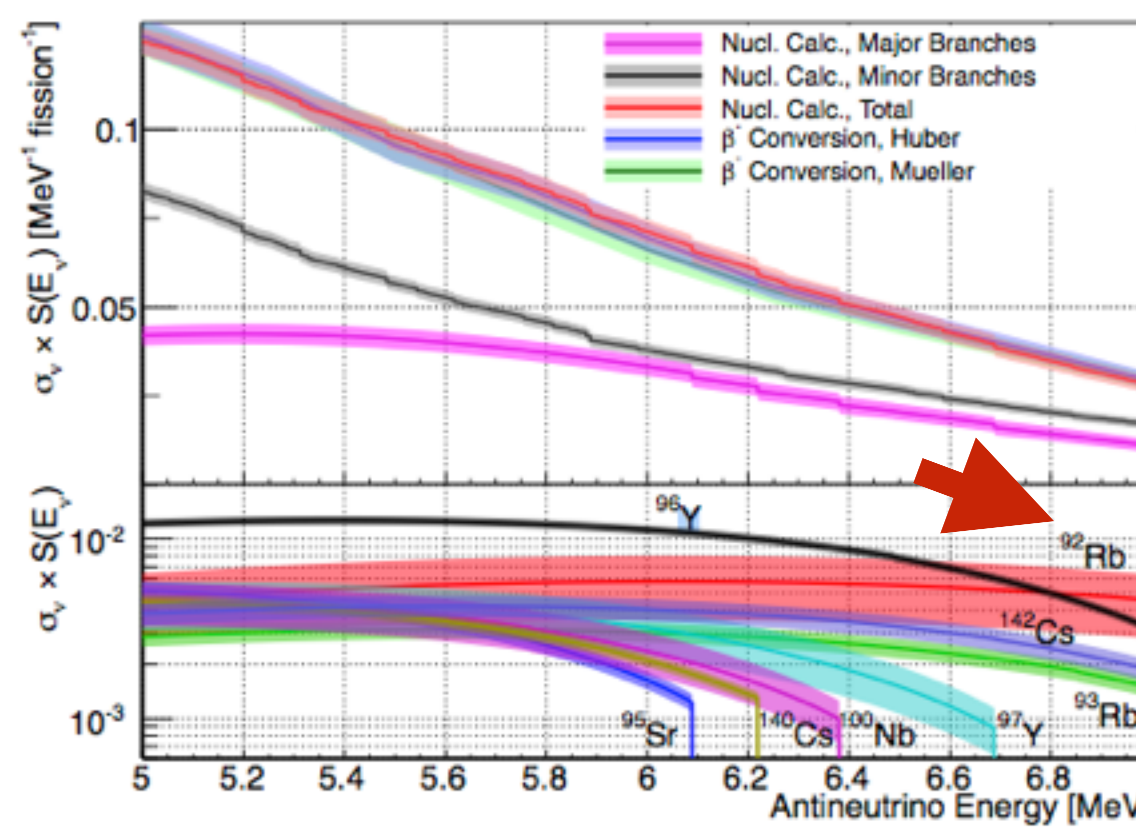


- If branching ratios are known better, decay released in those decays will be modelled better
- Better model = smaller safety factor = $$$ saved.

Reactor Spectroscopy: Implications

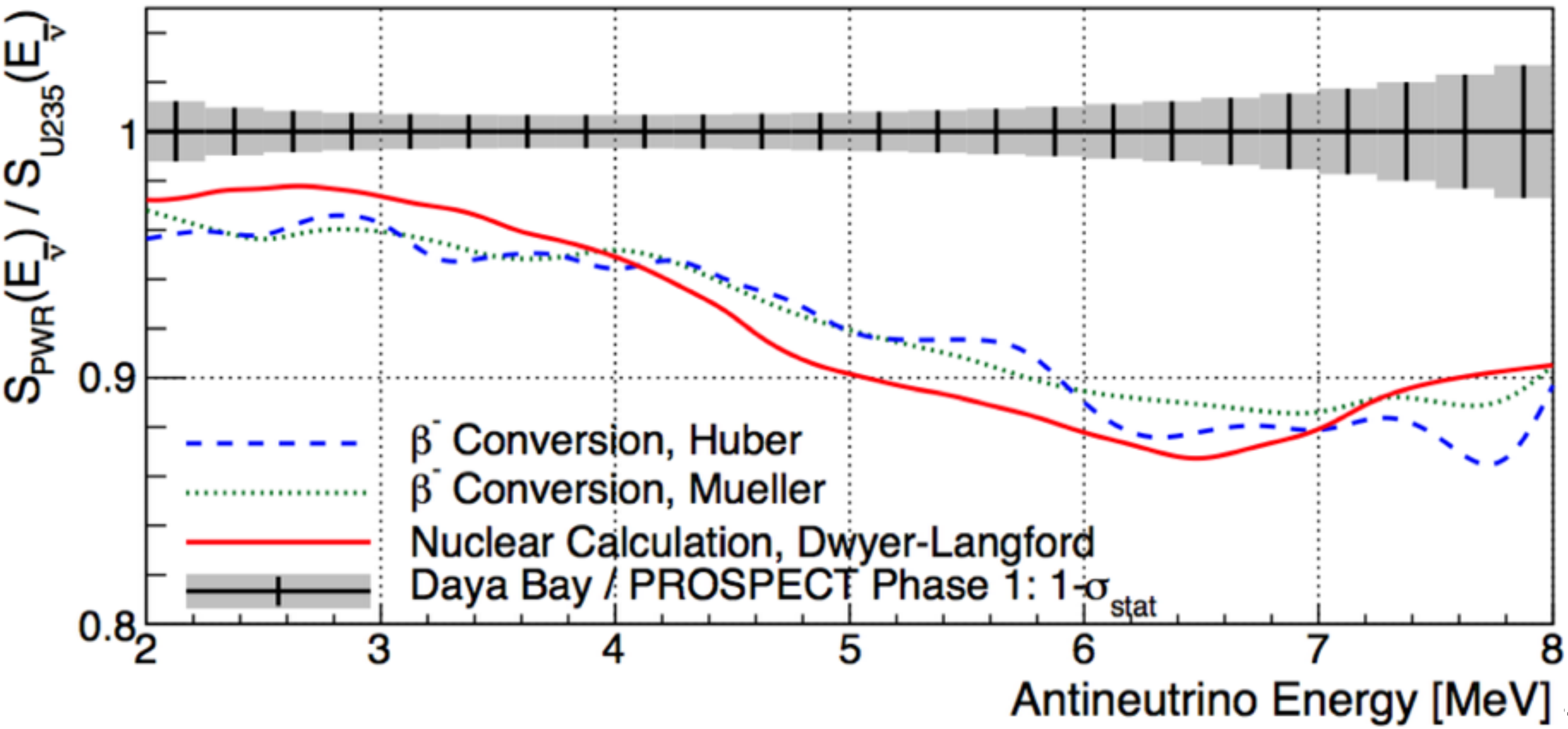
- 5 MeV 'bump' region produced by many isotopes of great concern to this decay heat measurement!
- Two anomalies from the same source?
- Reactor spectroscopy measurements can provide:
  - Direct check on existing TAGS measurements
    - TOTALLY different systematics!
  - NEW data if TAGS has not been done!
  - Isotopes: Rb-92, Sr-97, Cs-142





Spectrum Measurement HEU:LEU

- HEU-LEU difference, made more explicit:
  - ~10% difference in spectra between low and high energies
  - Extent of this difference depends on exact modeling
    - Ab initio: Predicts larger HEU-LEU spectral variation
    - Larger LEU-HEU variation in spectra: better for non-proliferation!!



Formulas for Energy Reconstruction

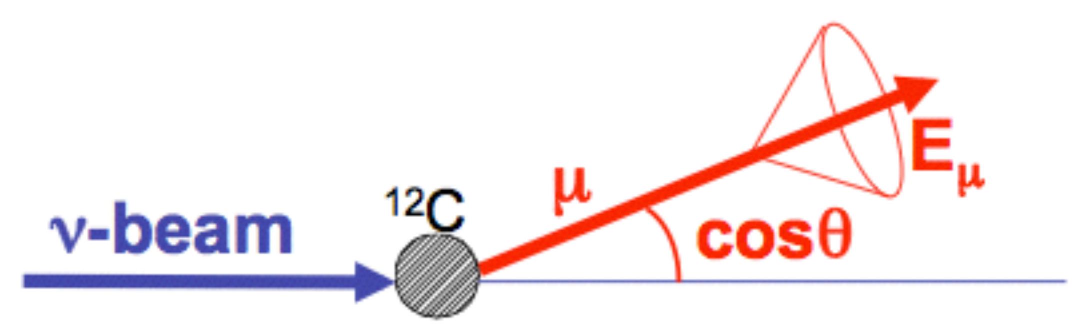
- Daya Bay
  - Minimum energy of 1.8 MeV needed to make neutron and positron
  - Momentum conservation means positron gets almost all kinetic energy

$$E_{prompt} = E_{\overline{\nu}_e} + (m_n - m_p) + m_{e^-}$$

- MicroBooNE
  - Not such a simple picture at higher energy; both target an lepton get significant amounts of momentum
  - In addition, interacting proton is bound in a nucleus
  - Need to measure lepton energy AND angle to get neutrino energy

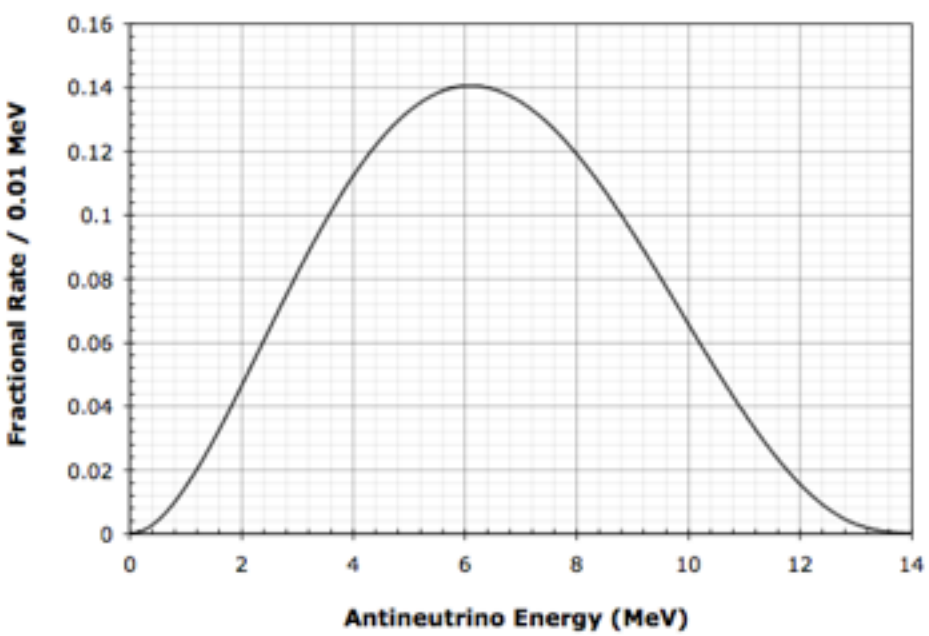
$$E_\nu^{QE} = \frac{2(M - E_B)E_\mu - (E_B^2 - 2ME_B + m_\mu^2 + \Delta M^2)}{2[(M - E_B) - E_\mu + p_\mu \cos\theta_\mu]}$$

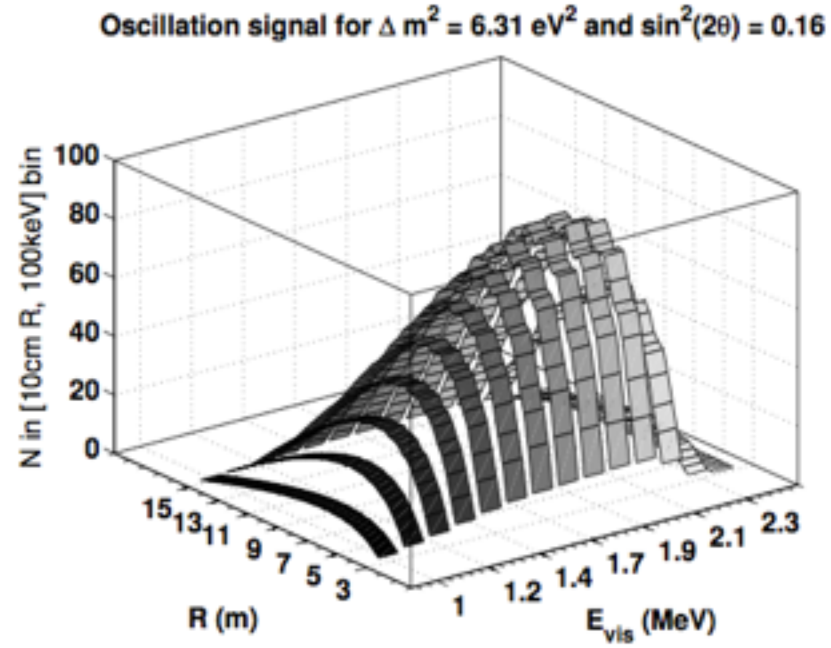
$$Q_{QE}^2 = -m_\mu^2 + 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu)$$



Competing Efforts

- CeLAND and SOX: Radioactive source experiments: quick-ish
- IsoDAR: Accelerator-produced beta decay source: longer timescale

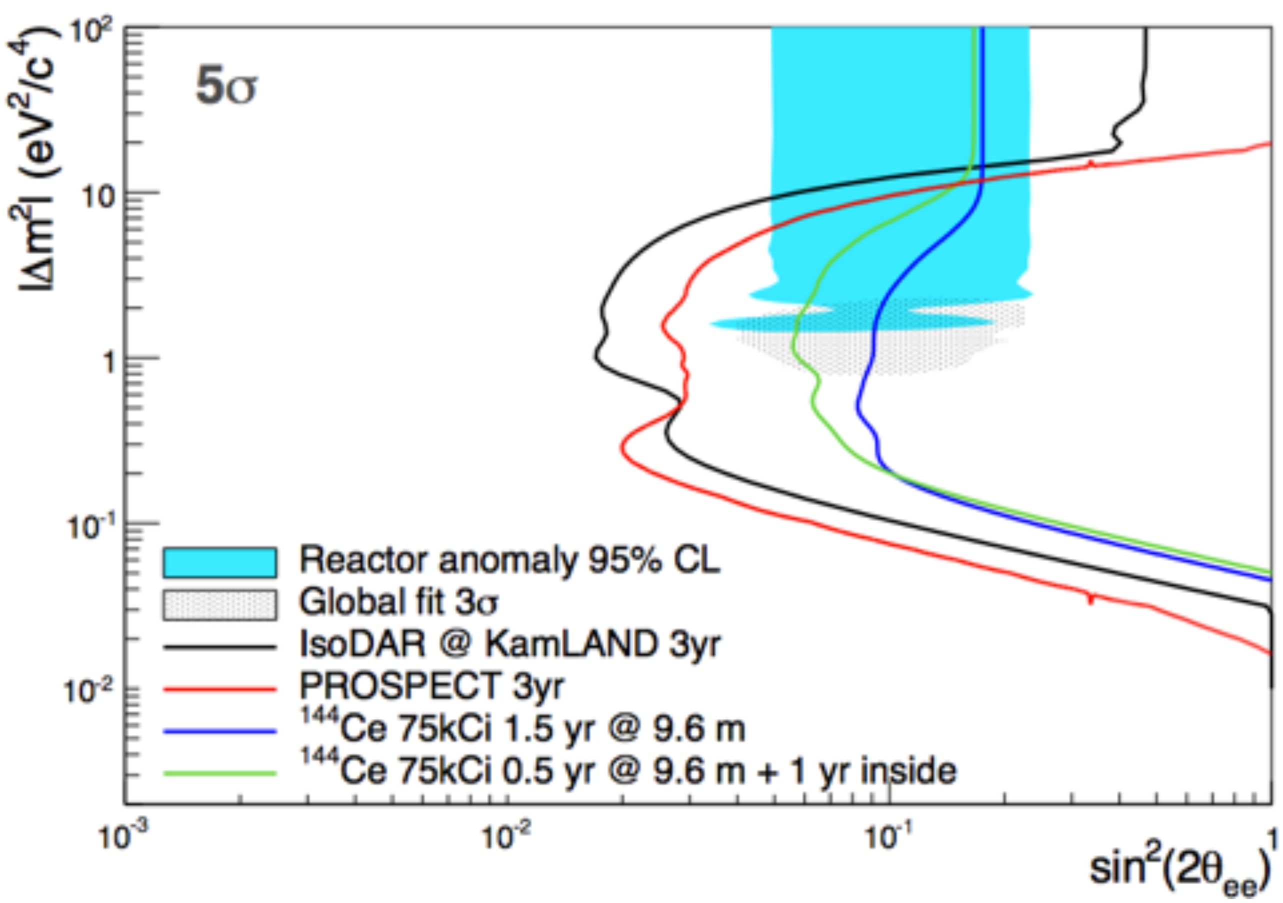


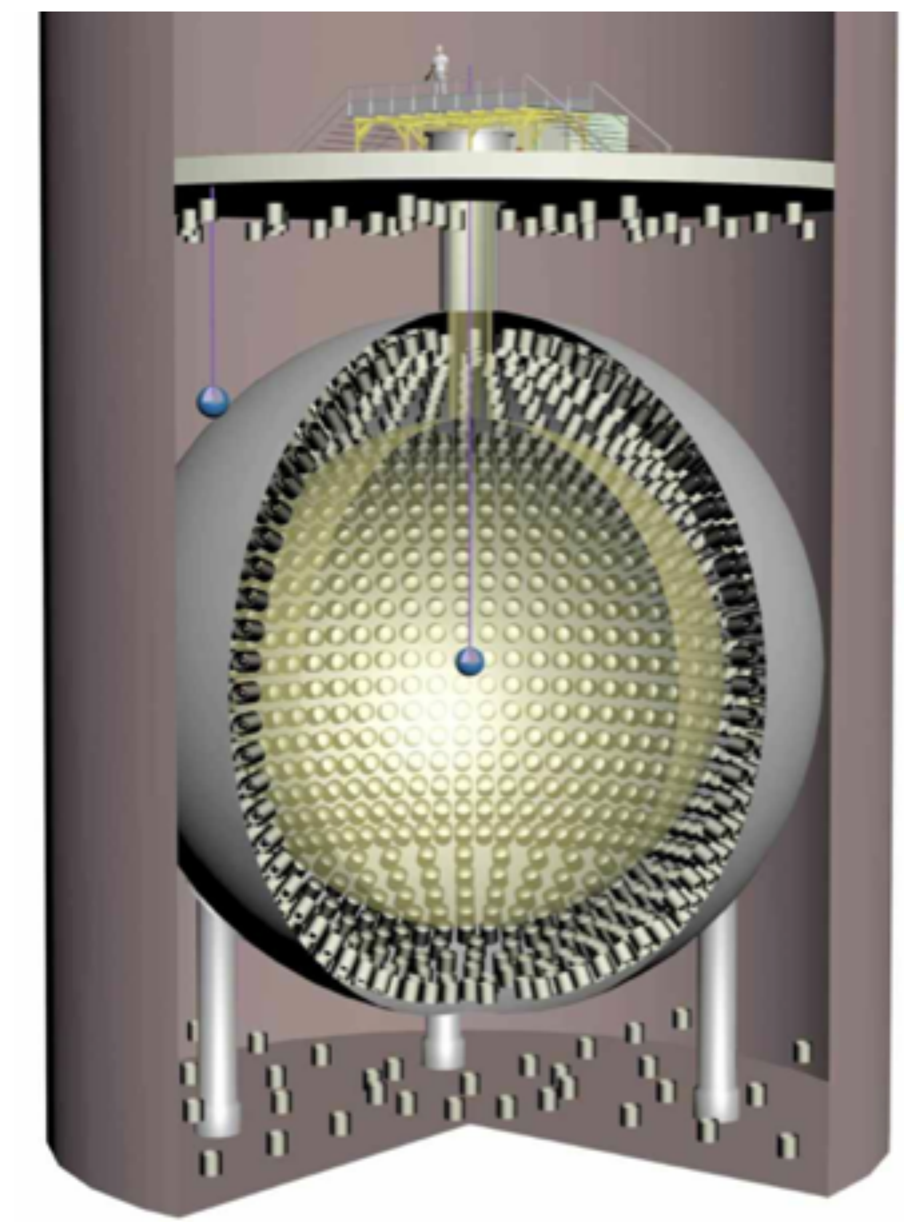


arXiv:1312.0896

arXiv:1307.2949

arXiv:1304.7721

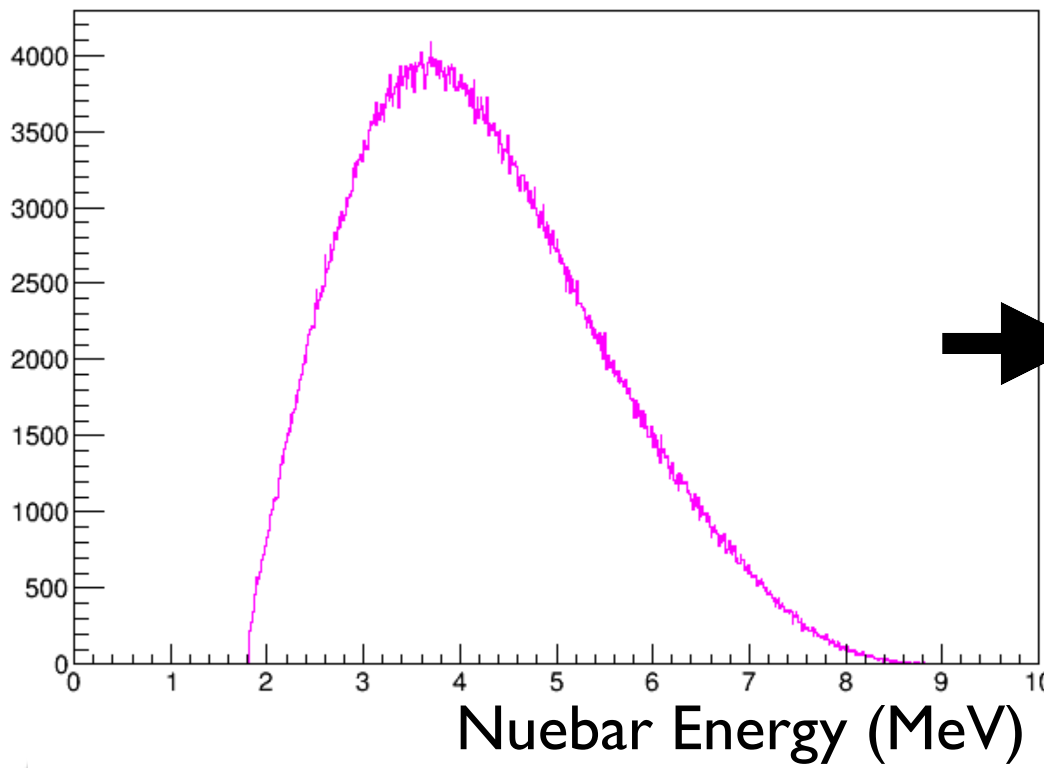


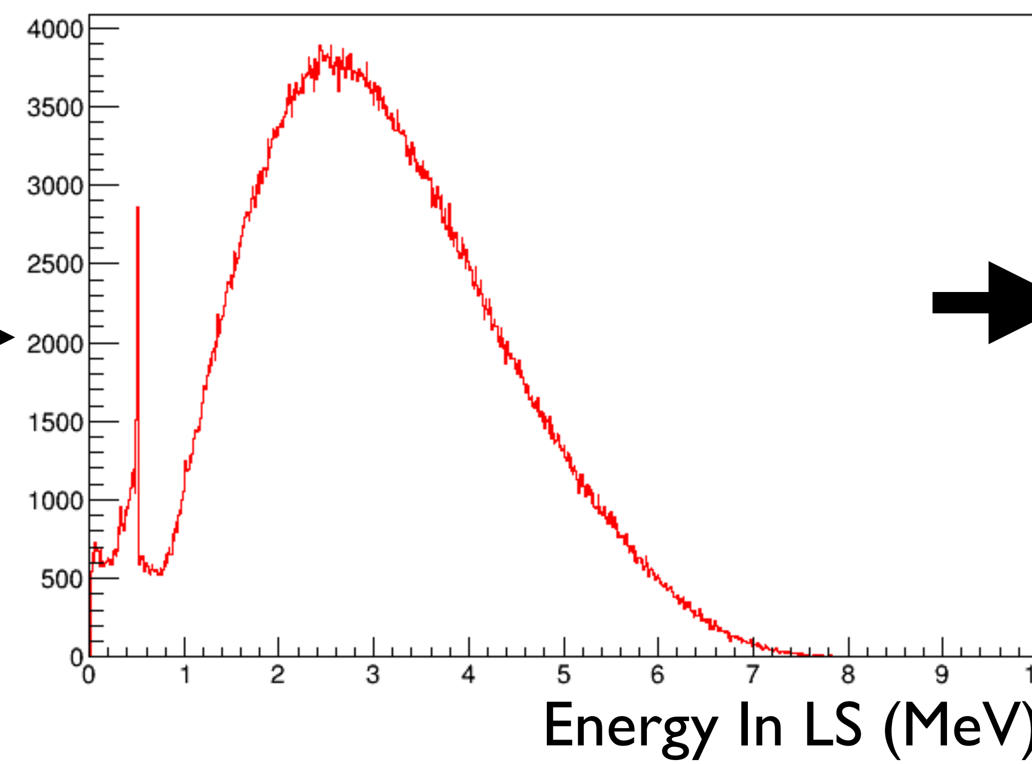


IBD Detector Response: Simulation

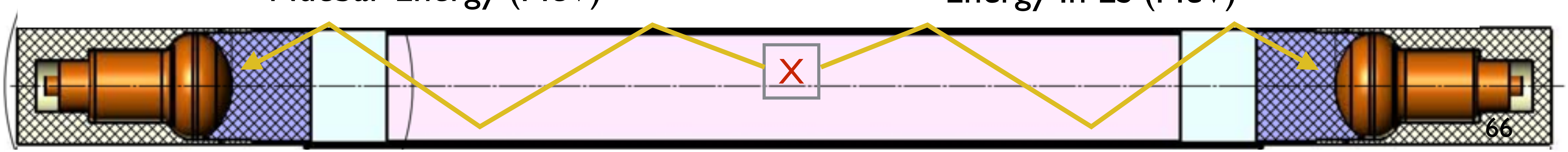
- Must reconstruct e^+ energy with high resolution and low bias
- Model response with lab-benchmarked simulations
  - Energy deposition outside LS
  - Normalization and linearity of light production, collection, etc. with energy
  - Light yield variations along cell
  - Variations between cells

PROSPECT detector simulations





Optics simulations, Relative cell response simulations underway



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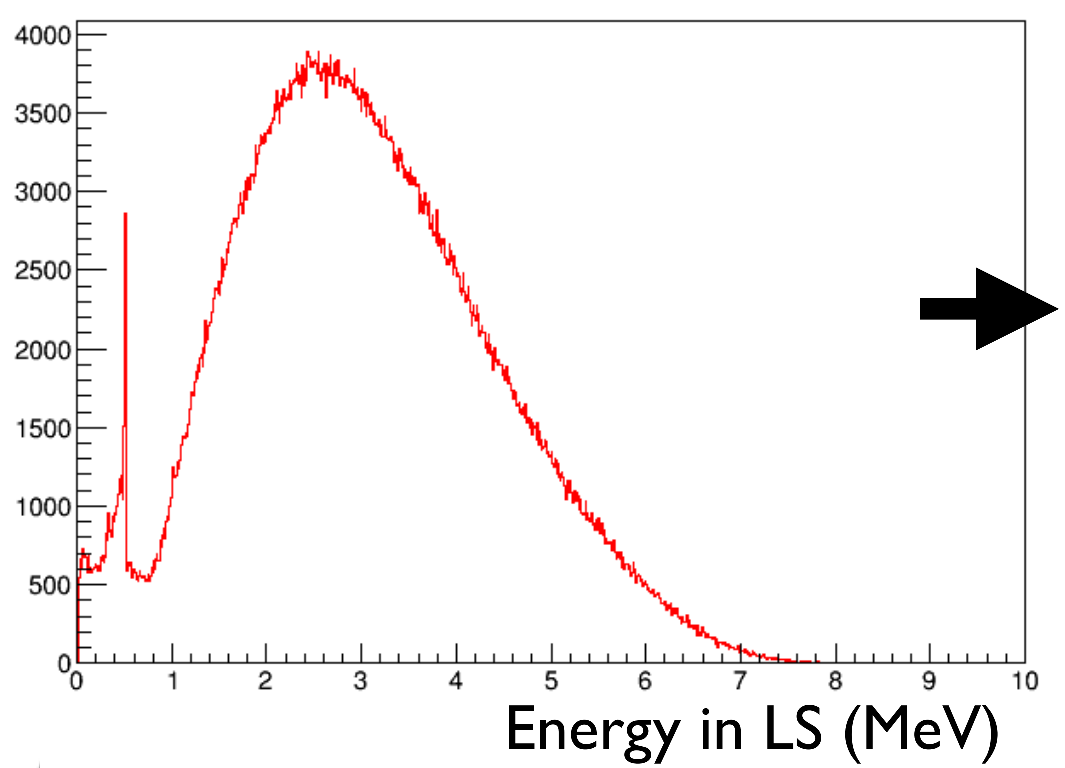

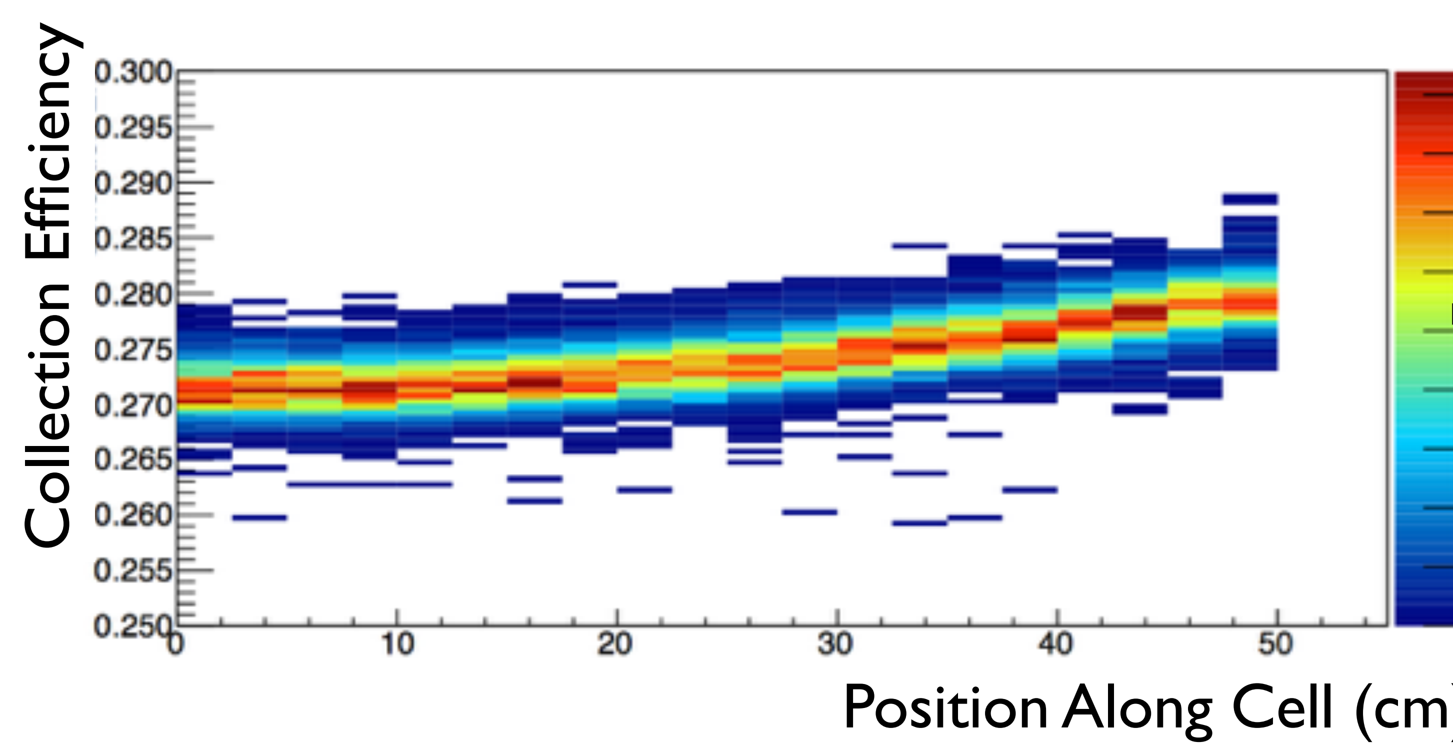

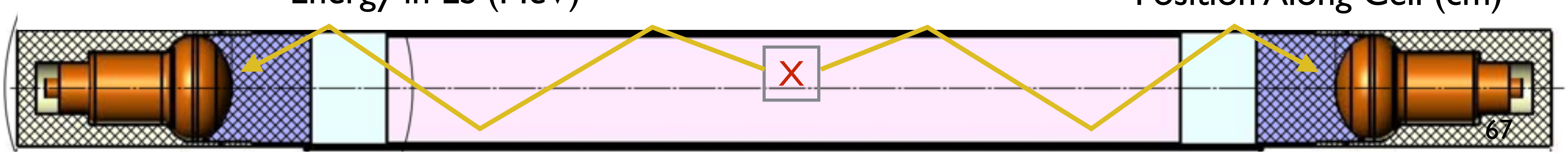

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